NOVEL DISTANCE RELAYING SCHEMES FOR THE PROTECTION OF EHV/UHV TRANSMISSION LINES USING DIGITAL TECHNIQUES

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By

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to the

DEPARTMENT OF ELECTRICAL ENGINEERING

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DEDICATED TO

My Beloved Father Late, Dr. J.B. Kellogg,
Mother Mrs. I.B. Kellogg, my Wife and
Children and my elder brother Dr. S.P. Kellogg

EE-1984-D-KEL-NOV

CERTIFICATE

It is certified that this work entitled 'NOVEL DISTANCE RELAYING SCHEMES FOR THE PROTECTION OF EHV/UHV TRANSMISSION LINES USING DIGITAL TECHNIQUES' by Mr. Anug Jaiprakash Kellogg has been carried out under our supervision and that this work has not been submitted elsewhere for the award of a degree.

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– A.J. Kellogg

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$S_1, S_2, \ldots S_n$	-	Sinusoidal relaying signals
$S'_1, S'_2, \ldots S'_n$	-	Relaying signals after standardisation through Op-Amp. etc.
V, V_L	-	System fault voltage refered to P.T. secondary.
I, I_L	-	System fault current refered to C.T. secondary
R, R_R	-	Replica arc resistance
X_R, X_L	-	Replica reactance line reactance
Z, Z_L	-	Impedance seen by relay
Z_S	-	Source impedance
Z_R	-	Replica impedance
$k, k_1, k_2, \ldots k_n$	-	Constant of proportionality
α	-	Phase angle between signals
$\beta_o, \beta_1, \beta_2$	-	Angular limits of phase comparison
f_o, f_1, f_2	-	Clock frequency
θ	-	Replica impedance angle
ϕ, ϕ_L	-	Line impedance angle
Z_{R1}, Z_{R2}, Z_{R3}	-	Replica impedance of zone-1, zone-2 and zone-3 respectively.
a, b, c,	-	Three phases
V_a, V_b, V_c or V_{ra}, V_{rb}, V_{rc}	-	V.T. secondary phase voltage at relay location
V_{fa}, V_{fb}, V_{fc}	-	Phase to ground voltage at the fault point
V_x, V_y, V_z	-	Compensated line to ground voltages at the relaying point.

E_a, E_b, E_c	- Phase to ground voltages at the source point.
I_a, I_b, I_c	- Phase currents refered to C.T. secondary
I_{ao}	- Zero sequence phase current through transactor
1,2,0	- Positive, negative and zero sequence components
n	- Z_{L0}/Z_{L1}
K	- n-1
C_T	- Ratio of primary current to secondary current of main current transformer
P_T	- Ratio of the primary voltage to secondary voltage of main potential transformer.
E	- Relay voltage with zero source impedance

SYNOPSIS

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NOVEL DISTANCE RELAYING SCHEMES FOR THE PROTECTION OF EHV/UHV TRANSMISSION LINES USING DIGITAL TECHNIQUES

The demand of the electrical power in many countries of the world, has been increased manifolds during the last two decades due to the rapid growth of industries and also agricultural, commercial and domestic needs. Thus, large Thermal, Hydro and Nuclear power plants were installed, generally, far away from the load centres. This necessitated the transfer of bulk power over long distances by means of transmission lines and interconnectors. The reliability, durability and the stability of the power system network depends how fast and efficiently, the fault can be cleared. The transmission line voltage, in the past, was limited to 220 kV and hence, the protection schemes based upon the 'Induction Cup Relay' were satisfactory as the fault detection

within 2 to 3 cycles did not create any serious stability problem. The increase in the system voltages to 400 kV and above necessitated the detection of the fault in less than one cycle (20 msec.) which is beyond the capabilities of electromechanical relays. This gave rise to the development of static relays and finally, to the solid state relays. Solid state relays have distinct advantages over electromechanical and also other types of static relays that, they are fast in operation, sensitive, accurate, compact and immune to vibrations and shocks due to external causes. Absence of moving parts and contacts makes them more reliable and also long lasting. Negligible maintenance is needed once they are put in service, their burden is low and also they do not require high voltage supply. All these factors make them economical in the long run.

The distance relays used so far, for the protection of EHV/UHV transmission lines (400 kV and above) use discreate components like, diodes, transistors, TTL logic gates and analogue techniques. Some of them use digital components also but, they all suffer from the serious drawback of having different operating time depending upon the reach of the relay and the phase difference between the selected input signals. This can create serious time coordination problem between

different relaying schemes as the operating time varies between 10 to 50 msec. ($\frac{1}{2}$ to $2\frac{1}{2}$ cycles). Most of the relays generate classical threshold characteristics which could be prone to power swing in the case of long, heavily loaded transmission lines. Quadrilateral characteristic is most compatible to any type of line faults having high arcing resistance. Hence, modern trend is to use relays having quadrilateral pick-up characteristics. A relay, once designed for a specific characteristic, cannot produce a different polar characteristic which may be required for some applications. The same relay may not function, both, as sine and cosine comparator.

The protection schemes for the transmission lines are quite complex and at the same time, they are not flexible and their prime cost also is quite high. Digital relays using Microprocessor and Minicomputer for 'On Line' distance protection of EHV/UHV transmission lines are much faster and also free from many drawbacks. But, their long time durability and reliability is not yet assertained and at the same time, they are not accepted by 'Protection Engineers' as a primary means of protection.

The distance relaying schemes based upon travelling waves phenomena have been designed and fabricated and the first of its kind is in use on 500 kV system of Bonneville Power Administration, U.S.A. This scheme seems to be the best

of all but, is highly sophisticated and uneconomical for small power systems. Hence, there is an ample scope for developing a protection scheme which is free from the most of the existing drawbacks.

Accordingly, the primary objectives of this thesis have been:

1. To present critical review of some important relaying schemes with respect to simplicity, circuit ability, reliability and flexibility in generating the various types of pick-up characteristics in the complex β-plane (i.e. R-X plane).

2. To develop novel high speed, reliable relaying schemes for single-phase, single-zone operation which could be used to produce any desired pick-up characteristic with constant operating time and can be used both, as sine and cosine comparators with minimum of hardware.

3. To design, develop ~~e~~ and fabricate a 3-zone single-phase relaying scheme, using CMOS logic gates and digital IC's, capable of producing any desired threshold characteristic with constant operating time (15 msec.) for fault at any point within the reach of the relay, by the use of 2-input comparators.

4. To design and fabricate a 3-zone polyphase relaying scheme with a new operational strategy, using multi-input comparators, to produce modified mho characteristic using blinders and a quadrilateral characteristic with 3-input signals only, and

5. To design and fabricate a 'Dynamic Test Bench' with 'point-on-wave selector' and to test the performance of the various proposed relaying schemes on it, with respect to operating time, accuracy, transient reach verses switching angle of fault current and range.

The salient features of the work reported in this thesis are as follows:

Chapter 1 presents a brief review of the important literature pertaining to the development of the distance relaying schemes cronologically. It also describes the need of better and faster schemes and gradual change from electromechanical relays to static and then finally, to the solid state relays.

Chapter 2 gives the critical review of some of the important relaying schemes which could be used for the protection of heavily loaded long transmission lines. A detailed study of these schemes is done and their merits and demerits are brought out. It is revealed from the close examination, that, all these schemes suffer in one way or the other. Thus,

there is a scope for the design and development of a relay which is free from the drawbacks of the existing schemes.

Chapter 3 starts with the proposed novel relaying scheme. It describes the theory, development and testing of the digital phase comparator relay using CMOS logic gates and digital IC's, which could be used, both, as sine and cosine comparator and generate many important pick-up characteristics used for distance protection. The relay uses 2-input, transient free, block average, symmetrical coincidence comparator and its hardware is kept to a minimum, thereby, giving economy, fast response and reliability.

Chapter 4 deals with the design and development of a 3-zone single phase relaying scheme using digital techniques. It presents a new operating strategy and a novel way of automatic zone changing and a novel way of providing signals for 3-zone operation. The present work is an improvement and simplification over the relay proposed earlier. CMOS logic gates and digital IC's are used to give better noise immunity. The relay uses 2-input, transient free, 90° block average coincidense comparators with constant operating time of 15 msec. any where upto the balance point. Variable angular critaria can be used by the change of clock frequency and, thereby, shaping the characteristics. Scheme-I provides the

classical characteristic in zone-1 and zone-2, but elliptical characteristic in zone-3.

The same relaying scheme is extended to work as a 3-zone polyphase relay by the triplication of single phase units. Multi-input comparators are used to produce modified mho characteristics as proposed by scheme-II. The scheme-III proposes a 3-zone polyphase relay which produces a quadrilateral characteristics by using 3-signals only. All these 3-schemes are effective for all types of shunt faults on 3-phase lines. The steady state and dynamic performance of these schemes is tested, phase-wise, and operation of 3-zone polyphase relay is found to be satisfactory.

Chapter 5 describes the design, development and the fabrication of a single phase Dynamic Test Bench, which is used to predict the performance of the proposed relays. It represents the scaled down model of the power system, with built-in 'point-on-wave selector' and digital time interval meter. Any type of fault condition can be simulated on it and, the relay performance, with respect to range and switching angle of fault current, can be checked. The overall accuracy of the dynamic test bench is better than ±5% and each unit has an accuracy of ±2%.

Finally, the concluding chapter 6 gives a brief review of the work reported in the thesis and suggestions for further scope of work.

CHAPTER 1

INTRODUCTION

The protection of high voltage transmission lines, by 'Induction Cup Relay', in the past, was found to be satisfactory as the large fault detection time (viz. 3 to 5 cycles) did not create serious stability problems. In many countries of the world, the demand of electric power increased considerably after the second world war, due to the rapidly growing industrial, commercial and domestic needs. This gave rise to the installation of large peak load and base load plants i.e. Hydro, Thermal and Nuclear plants and transmission of this bulk power to the industrial and urban areas. It is neither economical nor practicable to built large power plants in every city, thus, the exchange of power between different grid systems became necessary which is done by Interconnectors. In India, upto the year 1975, the transmission voltage was limited to 220 kV and hence, a slower speed protecting scheme using electromechanical relays was adequate. But, as the bulk power transmitted increased, it became necessary to have higher system voltages exceeding 220 kV and a much more faster protection scheme so as to keep the entire power system network in stability. Fault detection within half to one cycle

was not practicable with the electromechanical relays which led to the development of 'Static Relays'. Static relays were found to be superior in all respects having several advantages over electromechanical relays.

Static relays are immune to vibrations and shocks produced by external causes, due to the absence of moving parts. They are highly sensitive and hence, give better discrimination of fault with high degree of accuracy and speed. The absence of moving parts and contacts, make the static relay more reliable and long lasting. It is easier to manufacture them and minuturisation is also possible. Their burden is low and practically, no maintenance is needed which gives economy in the long run.

Over head transmission lines are one of the most vulnerable elements in the power system network because of its length and also consequent exposure to atmospheric hazards. Hence, it is not surprising that, a lot of research has been carried out in developing an efficient, reliable, fast acting and sensitive relaying scheme for the protection of the transmission lines. Because of the inherent drawbacks of the over current relays, such as, shifting of the balance point with the type of fault and also, with the change in generation capacity etc., the distance relays are invariably used for the

protection of EHV/UHV transmission lines. Distance relay, which measure the distance to the fault by measuring the impedance or certain component of the impedance at a given angle to the point of fault, is based upon sound mathematical theory with the result, its performance can be predicted well in advance. There are different varieties of distance relays, such as, plain impedance, angle impedance i.e. ohms, reactance, angle admittance (Mho), directional, and also their modifications including restricted, offset and modified relays. Any one of these relays or certain combination of these, with proper time coordination, is used for the protection of transmission lines.

The earlier attempts were to use static relays as a mere substitute of the electromechanical counter parts in order to produce different types of threshold characteristics. This was easily achieved by the use of electronics and static device. Later development proved, that, static relays have a better potential for developing special and complicated threshold characteristics which could not be produced by electromechanical relays. The simultaneous clearing of end zone faults within one cycle (< 20 msec) was accomplished, by electronic relays, using carrier frequency channel. But, the electronic relay could not compete in other applications due to high and continuous power demand for its heater (filament).

Then came the invention of 'Transistors' in 1948 which revolutionised the field of electronics. The vacuum tubes and thyratrons were gradually replaced by transistors and its use in other applications was a natural consequence. Hence, the static relays, using solid state components such as, diodes, transistors etc., dominated the field of protection after the year 1960, till the year 1975.

The use of EHV/UHV (400 kV and above) heavily loaded long transmission lines has put a stringent requirement on the pick-up characteristic of the static relays. The tripping area on the complex β-plane (i.e. R-X plane) has to be as narrow as possible so as to avoid its operation during normal loading and power swing. Thus, the ideal characteristic would be a quadrilateral one or a mho having blinders. These characteristics are easily provided by static relays using solid state components but they all have one general drawback, that, the operating time (10 to 50 msec) is dependent upon the fault location and the phase angle between the selected input signals. The faster speed of operation (< 20 msec) could be provided by the relays using digitals components, microprocessors and minicomputers etc. Microprocessors based, and minicomputers based relays are still in R and D stage; their long time durability and reliability is yet to be established and, they are not

yet recognised by 'Protection Engineers' as primary means of protection. Hence, there is an ample scope of developing a high speed relaying scheme, using digital circuits, having greater noise immunity and threshold limits.

1.1 OBJECTIVES AND SCOPE OF THE WORK:

The objectives and scope of the work reported in this thesis have been

1. To present a critical review of some of the important relaying schemes with respect to their simplicity, circuit ability, reliability, speed and flexibility in generating the various types of pick-up characteristics in the complex β-plane i.e. R-X plane.

2. To develope novel high speed and reliable relaying schemes for single-phase single-zone operation which would be used to produce any desired pick-up characteristic and can be used as a cosine or sine comparator with minimum hardware.

3. To design, develop and fabricate 3-zone single phase and polyphase relaying schemes, using CMOS logic gates and digital IC's, capable of producing any desired threshold characteristic with constant operating time (< 20 msec) at any point within the reach of the relay.

4. To design and fabricate 3-zone polyphase relaying schemes with a new operational strategy, avoiding the relay time coordination problem, and to give modified mho and quadrilateral characteristic with 3-input signals only.

5. To design and fabricate a 'Dynamic Test Bench' with 'point-on-wave selector' and test the performance of the various relaying schemes on this dynamic test bench with respect to operating time, accuracy, transient reach versus switching angle of fault current and range.

1.2 HISTORICAL REVIEW:

1.2.1 Electronic Relays:

The use of electronic relays for power system protection starts from the year 1928 onwards. In that year, Fitzerald [1] developed a scheme for pilot wire protection, Wideroe [2] in 1934 developed circuits for common types of protective relays using thyratrons while Loving [4] in 1949 gave refinements to these circuits. The developments of electronic relays upto 1948 was updated by Mcpherson, Warrington and McConnell [3,5] and these were further extended in later years by Barnes [6] Kennedy, Honey, Reedman, Dlouby, Cohen, Chevallier and Bergseth [7]. All these schemes employed thermonic values

appearance sp
and thyratrons and therefore, ~~therefore~~ wasteful of energy. A continuous and large power was required to heat the filament and at the same time, a high voltage supply was needed by plate and screen circuit. This makes the power source bulky, costly and short lived. The thermionic valves and thyratrons were themselves bulky and fragile and also, liable to generate noise and give rise to incorrect operation due to vibrations, shocks and transients. None of these were found to be reliable and durable and thus they were not accepted for common use and remained as researchers curiosity. They also never reached the commercial stage and had to be abondoned after the year 1955. However, their use in microwave or carrier frequency relaying for inter-zone tripping continued till 1970. Then came the invention of 'transistors' in 1948 which was perfected by 1950 and brought a revolution in the 'field of electronics'.

Transistors and junction diodes are solid state devices and have many advantages over their counter-part, i.e.,' the valve'.They are of small size, rugged, light weight and have only 3 or 4 electrodes. They do not require any heater supply and heating time hence, their operation is almost instant. They work on low power supply (1.5 volts only) and have, high conversion efficiency. They are also unaffected by vibration and shocks due to external causes and have very

high power gain. All these advantages makes them an ideal subsitute of electronic valve and thyratrons. Their use in static relays took place just after 1950 and many circuits using 'Amplitude comparator' or 'Phase comparator' were developed.

1.2.2 Solid State Relays:

The earliest distance relay was introduced by Adamson and Wedepohl [15,16] in the year 1956 which used a phase comparator giving mho characteristic. The first paper [15] gave the mathematical background required for developing various threshold characteristics, such as directional, ohm, offset impedance and mho, by the use of 2-input phase comparator using transistors. The dynamic test revealed, that, the transient overreach was beyond the tolerance. Hence, they refined the previous circuit and use dual comparators [16] to minimise this transient over-reach present in their coincidence - block average phase comparator. Rao [19] in the year 1959 did a detailed study, of using transistors for protection of polyphase systems by using amplitude comparators and phase sequence detection techniques, to bring out many important and practical circuits. Adamson and Talkhan [18], Dewey and Hodges [20] described a phase-comparison carrier relaying scheme using transistors. Dewey et.al. [24] and Caleca et.al. [25] in 1963

described directional-comparison pilot relaying schemes using solid state components, based upon block-spike phase comparison technique, giving mho characteristic. Giot et.al. [27] and Hahn [28] in 1964 described 3-zone relaying scheme using transistors,based upon block average phase comparison techniques. Mathews and Nellist [29] gave a general technique for drawing characteristics by using geometrical methods. All the methods cited above gave good results but, there was no solid mathematical background to predict relay performance, well in advance, in the event of close-up fault and operation on short lines.

Wedepohl [30] in 1965 developed an improved theory of 'polarised mho relay' which gave better performance on short transmission lines and close-in faults and also, was more compatible to the actual system conditions. In the same year, Humpage and Sabberwal [31] gave a general technique to get any desired characteristic by suitable logic and use of several 2-input comparators. They also introduced multi-input phase comparators to give near quadrilateral characteristics. Improved composite characteristic with 3-zone of protection was proposed by Hans Hoel et.al. [38]. This also overcame the time coordination problem as associated with the use of several 2-input comparators. It was possible to generate many

improved threshold characteristics such as modified mho (with blinders) and quadrilateral etc. The superiority of block average coincidence scheme was well established by that time, as they were less affected to spurious signals and had better transient performance. However, Parthasarathy [36,37,39] in 1966 proposed a 3-step distance relaying scheme using multi-input block-spike phase comparison technique by employing discreate component such as, transistors, diodes etc. for measuring and logic functions. The relay gave good performance for all types of shunt faults and was immune to power swing. Anilkumar and Parthasarathy [43] in 1967 presented mathematical background necessary for predicting the performance of multi-input sine comparators to produce conventional and quadrilateral characteristics. They [45] proposed a 3-step transistorised distance relay having quadrilateral characteristic and also, gave modification necessary for using it with carrier-blocking and carrier-tripping schemes. Jackson et.al. [47] in 1968 discussed the parameters and the limits of optimum dynamic design of block-average schemes using analogue techniques. McLaren [48], in the same year, devised a new sampling technique by which it was possible to have instanteneous comparison of relay inputs at any instant which also simplified the comparator circuit. Maleev [50] in the same year proposed a polyphase relay based upon

phase-sequence detection of four input signals. Vitanov [53] presented a complete relaying scheme for 3-zone protection using transistorised circuitry.

In 1969, Gupta [54] proposed polyphase relaying schemes using phase-sequence detection of selected input signals. Anilkumar [56,60] in 1970 devised a new technique of sampling, and using ferrite cores, in addition to solid state components, to simplify the relay circuit. Kincha et.al. [58] proposed a new technique of instantaneous amplitude comparison by signals derived from the primary line quantities. This eliminates the zero-crossing detector, delay units, sampling gates and amplitude pulse duration convertors. They [61] extended this technique to produce quadrilateral characteristic in forward direction only. Paithankar [59] devised a unique phase-sequence detector which could be used to produce symmetrical or unsymmetrical angular critaria. It used only three derived signals from two basic sinusoidal input signals. In 1972, Johns [63] gave generalised phase comparison technique for 2-input comparators. He [66] also extended this technique for the operation of multi-input comparator and described the procedure to obtain the settings. A near quadrilateral characteristic could be obtained by this method. In 1973, he [69] proposed variable characteristic generalised techniques for distance protection. Later he [79] extended this principle to distance protection of double circuit lines and lines with selective-pole autoreclosure.

Choudhuri et.al. [67] proposed a polyphase ground distance relay based upon phase coincidence detection of three compensated line to ground voltages. It worked well with all the ground faults having high arcing resistance and remained inactive for all phase faults. Bhattacharya et.al. [68] devised a polyphase relay, based upon 2-input sine comparators, which could cater for all ten types of line faults. Paithankar et.al. [70] in 1973, devised a very simple and fool proof polyphase relay, based upon phase-sequence detection of four selected input voltage signals, responding to all ten types of shunt faults but, the tolerance to arc resistance was very marginal. A single 2-input comparator is generally, not able to produce quadrilateral characteristic. However, Jackson [75] in 1974 has tried to shape the characteristic of a 2-input block-average comparator, to get near quadrilateral characteristic. One novel multi-input amplitude comparator is proposed by Paithankar and Ingole [80] which gave any desired quadrilateral characteristic with fast response. Basu et.al. [81] proposed a polyphase relay based upon phase sequence detection of any three compensated voltage or combination of compensated and phase voltages by using four pulse sequence comparator. In all, five inputs are required and the relay is suitable for any type of line faults. A much simpler version of the polyphase relay, based on detection of phase sequence of four selected input signals, was proposed by Patra et.al.[82]. They used transisto-rised zero crossing detector and flip/flops and AND gate to realise the complete relay for all ten types of shunt faults.

Vitanou et.al. [83] in 1974 discussed the advantages and problems of using the integrated circuits (IC's) for protective relays. The use of discrete components, such as transistors and diodes, reduce the reliability of the circuits and hence, their number is limited to 50 to 100. The use of ICs on the other hand increases the reliability, sensitivity and accuracy to about ten times. Hence their use, for protection system can give a response of 10 msec. or less with 1% accuracy and therefore, can dominate upto the year 1990. They also suggested a new design for distance protection, autoreclosure and high speed tripping devices. Verma et.al. [84], in the same year, suggested a new approach for the measurement of impedance by sampling the R and L of the lines using Hall crystal. They gave a block schematic diagram for realising quadrilateral characteristic in a novel way. Shamugasundaram et.al. [88] in 1976, introduced a hybrid comparator in which the instantaneous comparison of 3-input signals can generate conic characteristics which could be ideal for long transmission lines. El-Alaily [89] in 1977, proposed a modified distance relay which is based upon coincidence period of four suitably extracted voltage signals at the relay location.

All the relays mentioned above suffer, due to the increasing operating time, as the phase-comparison angle increases beyond 60°. The operating time becomes infinity at the boundary of the relay characteristic. The digital phase comparator proposed by Ramamoorthy and Lal [93] in 1979, is free from these drawbacks and also, from the time coordination problem. The authors claim it to be superior to the analogue comparator. In 1980, Parthasarathy et.al. [94] described an adaptable distance relay suitable for heavily loaded EHV transmission lines. It has an adaptive feature, that, the characteristic is narrow for the balanced and power swing condition but, expand during unbalance fault conditions. Ramamoorthy and Lal [95] proposed a multi-input digital phase comparator to produce a quadrilateral characteristic whose reach in X and Y direction can be changed at will. Paithankar and Thoke [96], in the same year, proposed a polarised quadrilateral relay which has swievelling characteristic in the event of ground faults and, is also, suitable for double end infeed lines. Weller et.al. [102] proposed a new technique of phase comparison. The relay inputs are squarewaved, treated as binary and AND compounded. The states of AND gate output will have a particular sequence over the operating angular range, which is completely different from that over the blocking range. The tripping sequence is determined by the aid of a

counter. Marttila [103] in 1981 proposed a new method of analysis for predicting the performance of polarised mho relay and the method is suitable for computer analysis also.

In all the above cited relays, the measurement of fault-impedance is done at steady state condition, hence, the operating time cannot be less than 10 msec ($\frac{1}{2}$ cycle) to achieve sufficient accuracy and limited transient over-reach. The relay based upon travelling wave phenomena, have operating time in micro-seconds as the direction of travelling wave is to be determined. A new 'Ultra-High-Speed Relay' based upon travelling wave phenomena is proposed by number of authors such as Yee et.al. [90], Chamia et.al. [91], Matele [99] and Carter [101] and can detect the fault in few msec. (<5 msec). The first one of its kind is in use at 500 kV system of BPA, USA and was installed in 1976 and seems to be best of all schemes. In 1981, Deshikachar et.al. [104] proposed an improved scheme based upon travelling wave phenomena using a simple technique for choice of signals and tripping condition. They [109] also proposed a single phase, 3-zone, distance relay using TTL logic and many pulsing circuits which made the circuit complicated and prone to spurious signals. In 1983, Basu et.al. [113] devised a simple and effective method for the protection of series compensated lines. It uses a 4-input phase sequence detector to produce 2-quadrilateral characteristic by the use of transistorised logic gates.

Now, the chapter wise description of the work reported in this thesis is given.

1.3 CHAPTER WISE DESCRIPTION:

Chapter 2 gives the 'critical review' of some of the important relaying schemes which could be used for the protection of heavily loaded EHV/UHV transmission lines. A detailed study of these schemes is done and their merits and demerits are brought out. A close examination reveals, that, all of them suffer with respect to simplicity, flexibility, compactness of circuit and performance of the relay. They, generally use analogue technique and hence, the operating time is bound to vary depending upon the type and location of the fault. Hence, there is an ample scope to develop a relay, using digital techniques, which give constant operating time.

Chapter 3 presents the new relaying scheme developed in this thesis. It describes the design, development and testing of the transient free, 2-input, block average, digital phase comparator relay using CMOS logic gates and digital IC's. The relay has constant operating time of 15 msec. and is immune to noise and spurious signals and power swing. The relay could be used both, as sine and cosine comparator, thereby, giving flexibility and economy. It can generate many important pick-up. Characteristics, such as, directional, restricted directional, angle impedance i.e. ohm, reactance, plane impedance, angle admittance i.e. mho, offset mho and

elliptical and restricted characteristics etc. The operation of the relay is very simple and the hardware is kept to a minimum, which makes the relay economical, compact and more reliable.

Chapter 4 deals with the design, development and the fabrication of a 3-zone single phase relaying scheme with a new operational strategy which could be used for the protection of the EHV/UHV transmission lines. The present work is an improvement and simplification of the work reported earlier. CMOS logic gates and digital IC's are again used to give better noise immunity. The relay circuit is the extension of the work reported in the previous chapter. The signals are provided in a novel way and, the zone changing is done automatically due to zone time control. The operating time remains constant (15 msec) and varies slightly with fault current switching angle. The same relaying scheme could be extended to become a 3-zone polyphase relay, simply, by tripplications of each phase module and OR gating the final trip signals of each units. The scheme-I, using 2-input comparators, for polyphase relaying, gives the classical characteristics.

The scheme-II and III, used for polyphase relaying, are based upon multi-input comparators and are effective for all the ten types of faults on three-phase systems. The 2-input

comparators are converted to multi-input comparators by the use of AND and NOR gates. The scheme-II produces a modified mho characteristic with blinders, by the use of 3-input signals only. The scheme-III produce a quadrilateral characteristic by the use of 4-inputs to each comparator but the fourth input is derived from same 3-signals. The dynamic performance is tested phase-wise and the operation of the polyphase relay is found to be satisfactory.

Chapter 5 describes the design, development and fabrication of a single phase Dynamic Test Bench which is used to predict the performance of the proposed relays, both, in steady state as well as in dynamic conditions. It has a built-in 'point-on-wave selector', phase angle meter and the digital time interval meter to measure the relay operating time with respect to switching angle of fault current. The dynamic test bench is self contained and can simulate all the fault conditions on a power system network.

Finally, the Chapter 6 concludes by reporting the salient feature of the work done in the thesis and outlining the suggestions for future scope of work to be pursued in this field.

CHAPTER 2

PROTECTION SCHEMES OF EHV/UHV TRANSMISSION LINES USING SOLID STATE COMPONENTS

2.1 INTRODUCTION:

There are several schemes for the protection of high voltage transmission lines by using static relays. Some are based upon old faithful~~l~~ 3-zone protection by polarised mho relay. These schemes required 3-sets of phase fault relay and 3-sets of earth fault relay. Rectifier bridge phase-comparators were used with operating time of about 2-cycles. Later schemes used 'Switched distance schemes' in which 'fault detectors' are used to connect the signals from faulted phase to the common relay. This also gave mho characteristic with operating time of 25 to 40 msec. over most of the range. Modern trend is to use relay with quadrilateral characteristic as it is compatible with any type of line fault having high arcing resistance.

Various schemes, as cited in the current literature, are studied in detail and their merits and demerits are brought out. A critical review of few of the important relaying schemes is reported in this chapter. These schemes show the gradual developments upto date. The main aim of the critical review of the different schemes is to develop~~e~~ a relaying scheme which is

free from the existing drawbacks and at the same time, it could be flexible, having simple circuit and minimum hardware.

All the existing relays are, basically 'Comparators', which can be either-phase, amplitude, composite, digital or directional comparators. These comparators are critically reviewed in the following paragraph.

2.2 PHASE COMPARATORS:

These relays give an output signal (i.e. trip signal) when there exists a phase difference, between 2 or more relaying quantities, within certain specified limits. Ideally, the output is independent of their magnitudes. These relays are capable of generating any type of threshold characteristics such as directional, plain impedance, angle impedance i.e. ohm, reactance, angle admitance i.e. mho, offset mho, modified and restricted characteristic and quadrilateral etc.

Static relays have certain advantages over the electromechanical relays. They are compact, light weight and impose low burden on C.T. and P.T. They are not affected by external causes such as vibrations and shocks etc. as they do not have moving parts; which also make them fast in operation and free from contact racing problems. Static relays can give trip signal in less than one cycle which is essential for increasing the transient stability of the power systems. They are also more sensitive reliable and accurate and have better

threshold characteristic. Static relays using solid state components are far superior to the Electronic relays as the power requirement is very low and they are more sturdy and compact. It is easier to manufacture static relay and miniturisation is also possible.

The phase comparators giving impedance characteristic is non-directional and also has large tripping area with the result that it is liable to operate during power swing. This drawback was overcome by the development of mho relay and it was found most suitable for EHV line such as 400 kV lines etc. However, when power demand increased, the lines were heavily loaded which made it prone to power swings. Thus a much narrower characteristic was required which ultimately made use of modified mho or restricted mho relay. The best results were obtained with relays giving quadrilateral characteristic.

The quadrilateral characteristic is most compatible with any type of line fault including the effect of fault (i.e. arcing) resistance as it has minimum trip area. Hence, it is the desired characteristic for the long and heavily loaded EHV lines, as the relay will not operate due to power swing and is also insensitive to the fault resistance.

Single-phase switched distance relaying schemes were employed in the past, but they used more comparators, switching device and a fault detector. The relay was rendered inactive

in the event of failure of fault detector and switching device which gave rise to the development of 3-phase relay. Three-phase relay has the distinct advantage that it is immune to power swing, balanced load condition and sudden overloads. Polyphase relay can be either, phase relay, ground relay or combination of both. All modern three-phase relays use solid state components for fast operation. If the relay operation is very fast (< 5 msec), then it is prone to transients and overeach, if the operation is slow (> 20 msec), the transient stability is poor. Hence a compromise is to be made for better accuracy, reliability and fast response. This has resulted in various designs, choice of proper relay signals and relaying techniques.

Since several types of novel phase and ground relays as well as three-phase relays are developed in this thesis, it is desirable to give critical reviews of existing static relays so as to compare their merits and demerits and need for the development of such new types of static relays with several distinct merits.

2.2.1 Polarised Mho Distance Relay [30]:

Operating Principle:

The polarised mho relay (p.m.r.) requires 3-input signals for its operation, though the final comparator is a 2-input one. These signals are: (i) operating input (I_L),

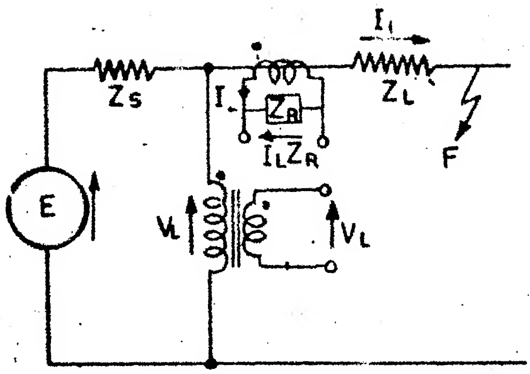


Fig.2·1(a) SYSTEM & RELAY CONNECTION

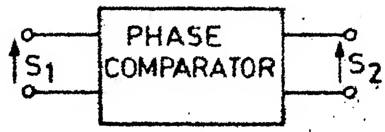


Fig.2·1(b) COMPARATOR INPUTS

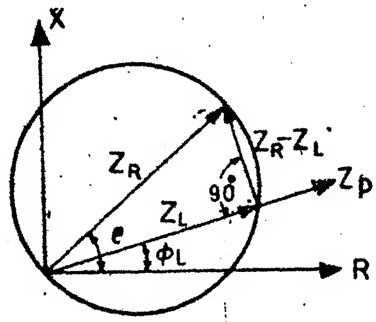


Fig.2·1(c) VECTOR DIAG (Vp ∠0)

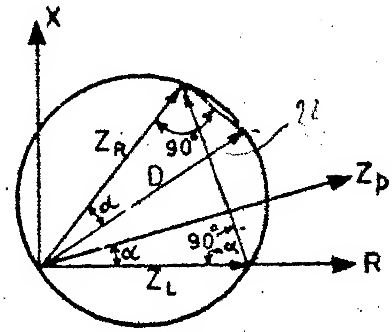


Fig.2·1(d) VECTOR DIAG (Vp ∠α)

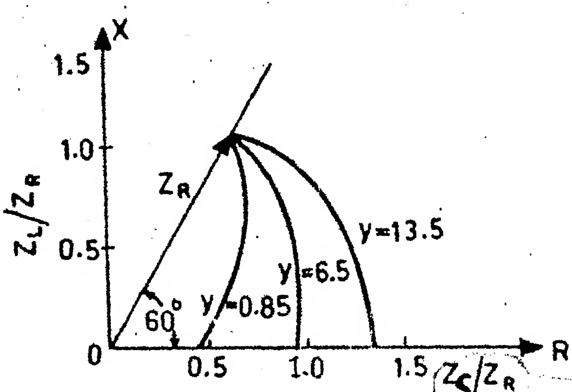


Fig.2·1(e) EFFECT OF Z_S ON POLAR CURVES

(ii) restraining input (V_L), (iii) polarising input (V_P). If this polarising input is also derived from the same faulted phase, then, the relay fails to operate for close-in-faults. If the polarising voltage is derived from other means, then, the relay can also remain operative for close-in-fault. The requirements for polarising voltage are:

a) The phase angle of polarising voltage should have a fixed relation to the restraining voltage, and

b) The magnitude of polarising voltage must be greater than zero even if, for terminal faults, the restaining voltage approaches zero.

In practice, it is not possible to satisfy both conditions and hence, a compromise is made in the selection of polarising voltage. Different methods in use are:

i) Faulty phase voltage with memory action

ii) Healthy phase voltage

iii) Residual voltage

iv) Residual current.

All these methods have been tried successfully but each has its own merits and demerits. Pick-up characteristics for different polarising inputs can be derived by mathematical analysis.

The merits of p.m.r. can be shown by considering the simplified theory as given below:

The inputs to the basic phase comparator relay are:

$$S_1 = V_P$$
$$S_2 = I_L Z_R - V_L \qquad (2.1)$$

where,

$$V_L = \frac{EZ_L}{Z_S + Z_L}$$

$$I_L = \frac{E}{Z_S + Z_L}$$

The Fig. 2.1(a) shows the basic connection of the relay and Fig. 2.1(b) shows the phase comparator inputs. If V_P is in phase with V_L then we can write:

$$S_1' = Z_P \qquad = S_1/I_L$$
$$\text{and} \quad S_2' = Z_R - Z_L = S_2/I_L \qquad (2.2)$$

where Z_P is the impedance due to polarising input V_P. The criterion for operation is:

$$-90^\circ \leq \angle S_1' - \angle S_2' \leq 90^\circ \qquad (2.3)$$

the vector diagram is shown by Fig. 2.1(c).

In practice V_P and V_L are not in phase for terminal faults due to Z_R/Z_L impedance angles. If the phase difference between V_P and V_L is α, which is generally not more than 15°, then, we have,

$$S_1' = Z_P \angle\alpha$$
$$S_2' = Z_R - Z_L \qquad (2.4)$$

The vector diagram for this case is shown by Fig. 2.1(d). Hence Z_R becomes a chord of mho circle where diameter of circle $D = |Z_R| \sec\alpha$. The polar equation for the circle becomes,

$$|Z| = |Z_R| \cos(\phi - \theta + \alpha) \sec\alpha \qquad (2.5)$$

The reach in the resistance axis for terminal fault ($\phi = 0$) is,

$$|Z| = |Z_R| \cos(\theta - \alpha) \sec\alpha = R; \qquad (2.6)$$

where R is the arc resistance.

Fig. 2.1(e) shows the polar curves by testing the actual relay based upon the detailed analysis where $\theta = 60^\circ$, $K_1 = 1.42$ and $K_2 = 0.14 \angle -15^\circ$. The curves are normalised and operating criterion being $\pm 75^\circ$. It can be seen that p.m.r. adjust its reach automatically for the arcing faults on short lines.

The salient features of the p.m.r. are:

1. The relay provides offset in the negative impedance quadrature//in the case of unbalanced faults. Thus it provides additional reach in the direction of resistance axis.

2. The relay characteristic for reverse power flow is a circle lying entirely in the negative impedance quadrature and not enclosing origin. Hence relay is directional.

3. The relay adapts itself to the system condition while retaining the ability of insensitiveness to the impedance due to load current and power swing.

4. The new theory developed is better than previous existing ones and hence, it is possible to predict the performance of the relay to the actual system conditions.

5. Derivation of polarising voltage and relay characteristics are available for different types of faults.

Drawbacks:

1. It is not possible to have fixed relation of phase angle between V_L and V_p, hence fault resistance problem always exists for the protection of short lines.

2. Due to high Z_S/Z_R ratio on short lines, there are chances, that, the relay may operate due to power swing.

3. For the proper setting, the angle between impedances Z_R and Z_L should not exceed 10°. This condition cannot be met with series capacitor compensated lines and hence setting becomes indeterminate.

Thus, there is a scope for a relay having better characteristic (viz. quadrilateral) which is compatible with any type of line faults and at the same time, immune to power swing.

2.2.2 Composite Polar Characteristics in Multizonal System of Phase-Comparison Distance Relay [38]:

The composite characteristics are based on the work done by Humpage and Sabbrewal [31]. Multizonal protection with improved characteristics are achieved by using suitable logic, phase comparator and zone-time control.

Operating Principle:

The operation of relay, based upon phase comparator, requires three essential circuit operations:

a) The derivation of rectangular waveform ,the width of which is a measure of phase displacement between the input relaying signals.

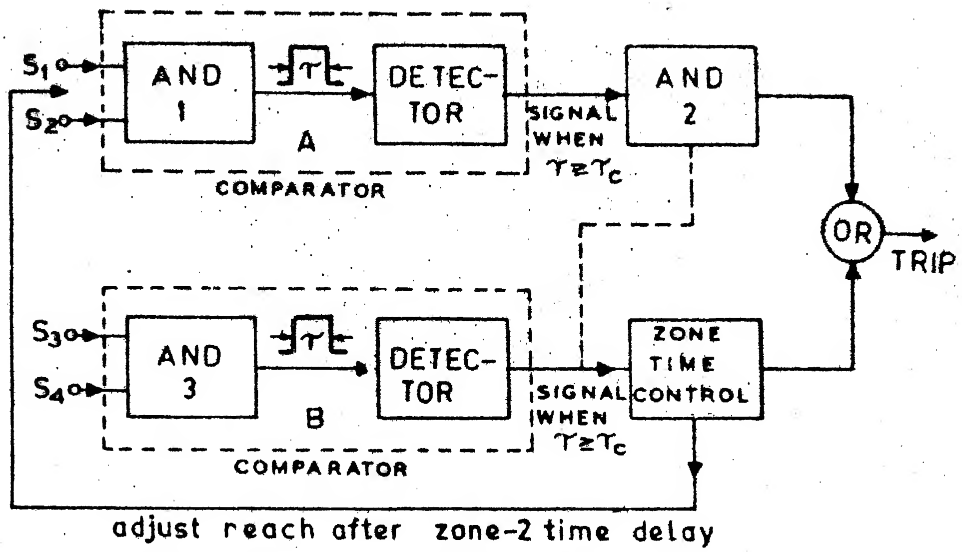
b) A means of detecting this width, corresponding to the phase displacement between the input signals, within predetermined angular limits.

c) Zone-time control and suitable logic for combining the individual characteristics and adjusting the reach of the relay.

Realisation of Composite Characteristics:

3-Zone Directional - Reactance Protection (2-Signal Comparison):

Figure 2.2(a) gives the block diagram of the protection scheme. Comparator A gives the reactance characteristics for zone-1 and zone-2 whereas comparator B is a mho type starting relay for zone-3. If the fault lies in the primary zone, then the relay trips directly within shortest possible



Comparator A → Reactance Relay

Comparator B → Mho Starting Relay

Fig.2.2(a) 2-SIGNAL COMPARISON

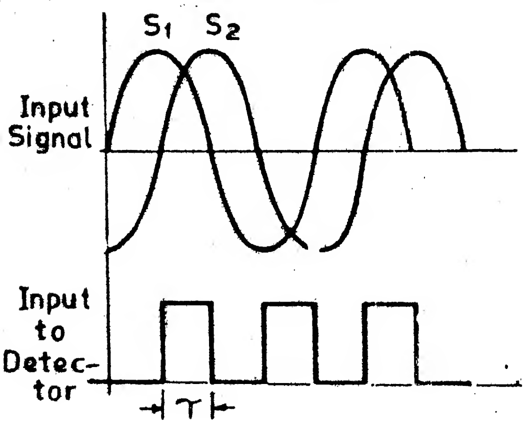


Fig.2.2(b) COINCIDENCE OF SIGNALS

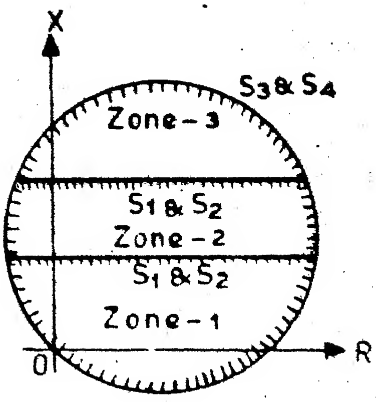


Fig.2.2(C) CHARACTERISTIC

time, otherwise after zone-2 time delay. The relay input signals and coincidence are shown in Fig. 2.2(b), and the characteristic in Fig. 2.2(c). In all there are four signals, as given below, to obtain the required threshold characteristics:

$$S_1 = -K_1 \angle\alpha_1 \, V_L + I_L Z_{R1} \angle \theta_1 - \phi_L$$

$$S_2 = I_L Z_{R2} \angle \theta_2 - \phi_L$$

give reactance characteristic

$$S_3 = -K_3 \angle\alpha_3 V_L + I_L Z_{R3} \angle \theta_3 - \phi_L$$

give mho characteristic.

$$S_4 = K_4 \angle\alpha_4 \, V_L \tag{2.7}$$

<u>3-Zone Mho Protection (Multisignal Comparison)</u>:

Figure 2.3(a) gives the block diagram of this scheme. Signals S_1 and S_2 give mho characteristic in zone-1 and zone-2, whereas signal S_3, S_4 and S_5 provide the characteristic of zone-3 with proper constraints. The final characteristic is a composite characteristic as shown in the Fig. 2.3(b). In all, there are five signals, as given below, to obtain the required characteristics:

$$S_1 = -K_1 \angle\alpha_1 \, V_L + I_L Z_{R1} \angle \theta_1 - \theta_L$$

mho characteristic for zone-1 and 2

$$S_2 = K_2 \angle\alpha_2 \, V_L \tag{2.8}$$

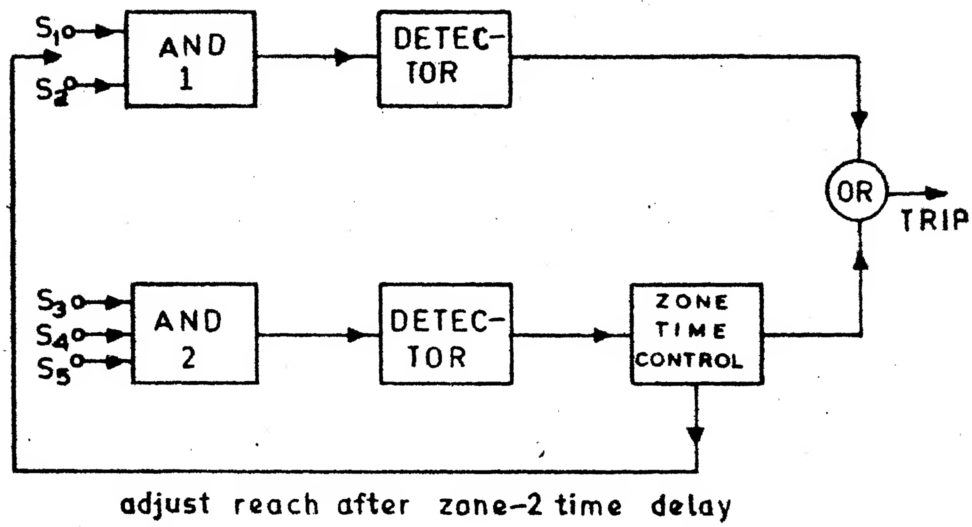


Fig. 2.3(a) MULTISIGNAL COMPARISON

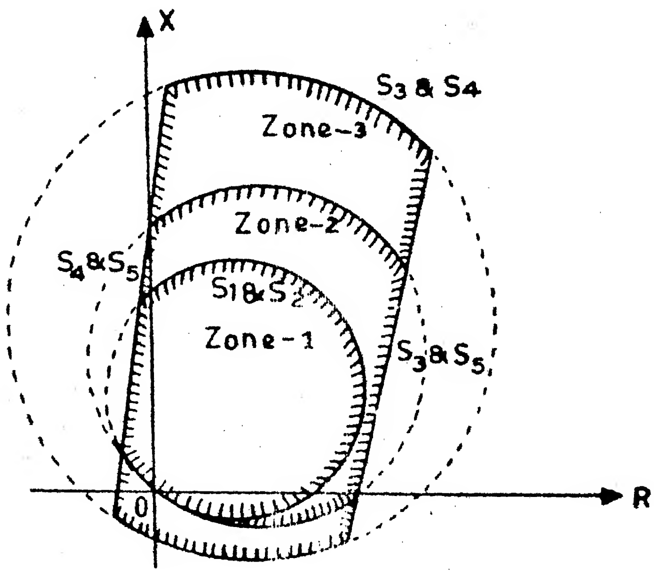


Fig. 2.3(b) CHARACTERISTIC

$$S_3 = -K_3 \angle\alpha_3 V_L + I_L Z_{R3} \underline{/ \theta_3 - \phi_L}$$
$$S_4 = K_4 \angle\alpha_4 V_L + I_L Z_{R4} \underline{/ \theta_4 - \phi_L}$$
$$S_5 = I_L Z_{R5} \underline{/ \theta_5 - \phi_L}$$

composite characteristic for Zone-3

The salient features of the protection schemes are:

1. Any desired characteristics can be achieved by suitable logic, using atleast two phase-comparators and independent control over the reach can also be provided.
2. The geometrical construction developed assist in the design of comparator input circuit.
3. A quadrilateral characteristic is feasible by using 2-comparators to secure independent control on the reach in the resistance and reactance axis. This enables the relay more compatible for any type of faults.
4. In a 3-zone scheme, mho characteristic is used for primary zone. The zone-3 characteristic is additionally controlled to provide long forward reach with immunity to power swing (elliptical characteristic).
5. Distance back-up protection using other controlled - tripping characteristic are derived and applications are given.

Drawbacks:

1. It is necessary to have time-coordination for proper relaying (tripping) which leads to increased response time.
2. The relay operation is sluggish one over the boundary faults.
3. The final relay circuit becomes more sophisticated by using these techniques.

2.2.3 New Static 3-Step Distance Relay [36]:

This scheme which was proposed by Parthasarathy, uses discrete components for different functional blocks and S.C.R. as final output device. The relay is suitable for long heavily loaded lines for all types of faults. The brief operating principle of this relay is given below:

<u>Operating Principle</u>:

The block diagram of the relay is shown in the Fig. 2.4(a) and the corresponding characteristics in Fig. 2.4(b). The multi-input comparator uses block-spike principle which provides the fastest measurement of direction and distance to the fault.

The inputs to the phase comparator are:

$S_1 = I_L Z_R$ (pulse at voltage zero) which is negative.

$S_2 = I_L R - V_L$

$S_3 = V_L \angle -90^o$

$$S_4 = V_L \qquad (2.9)$$

The $I_L Z_R$ pulse will appear at the output of comparator only, if, at the same time, all the three remaining input voltages are simultaneously positive. Criterion for operation and the characteristics are as follows:

i) $I_L Z_R$ pulse and $V_L \angle -90^o$ gives a directional characteristic with criterion for operation as $(\theta - 90^o) < \phi_L < (\theta + 90^o)$.

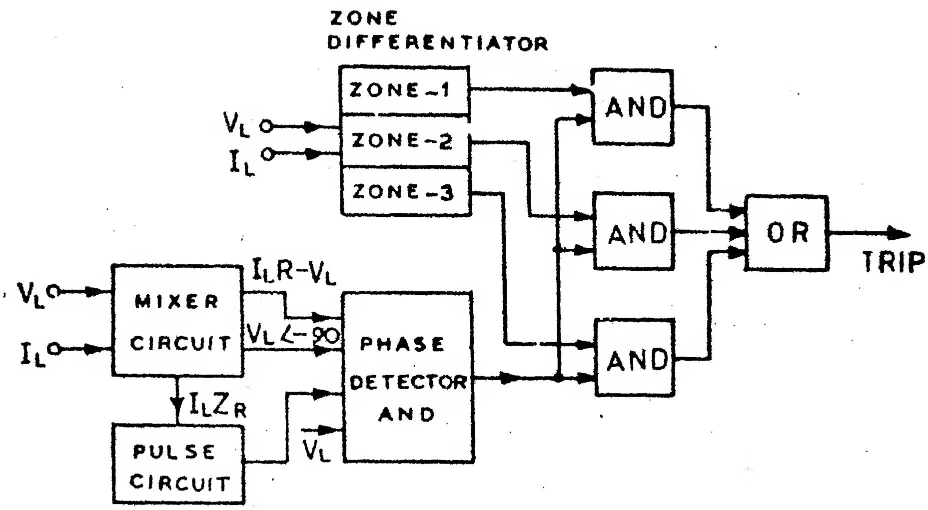
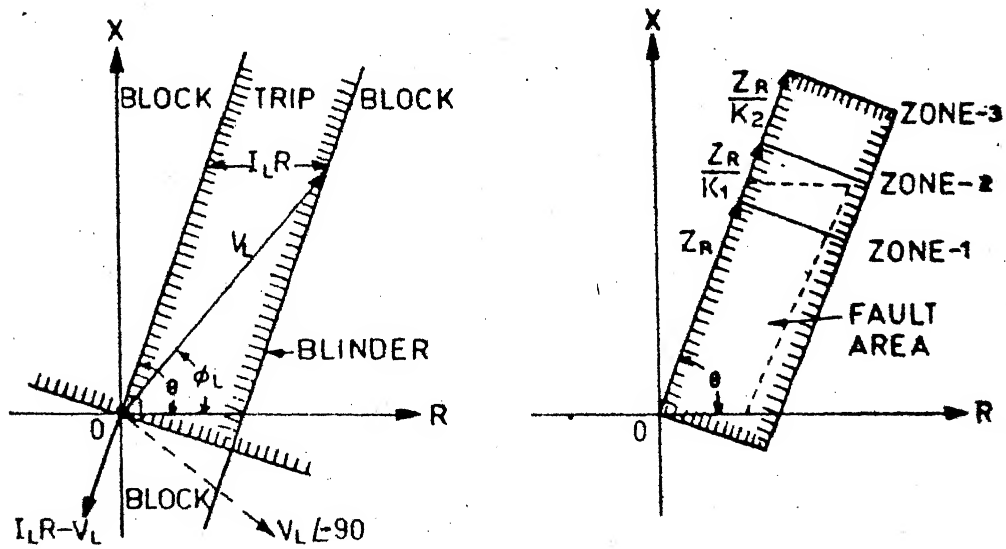


Fig.2·4(a) SCHEMATIC DIAGRAM OF RELAY



BLINDER CHARACTERISTIC RELAY CHARACTERISTIC

Fig.2·4(b)

ii) $I_L Z_R$ pulse with V_L and $(I_L R - V_L)$ gives blinder characteristic in the form of two parallel lines. Criterion for pulse to appear at output is:

$$\angle V_L < \theta < \underline{/(V_L - I_L R)}$$

or

$$\angle Z_L < \theta < \underline{/(Z_L - R)} \qquad (2.10)$$

The combined operation of above two comparison gives a polar characteristic, with three sides closed and open at the top. In the case of close-in fault when V_L disappears, $I_L Z_R$ pulse is gated by $I_L R$ and hence, positive operation is obtained.

The fourth closing side of characteristic is obtained by zone differentiating circuit. For faults within zone-1 reach, zone-1 AND gate opens at the arrival of $I_L Z_R$ pulse. For faults within zone-2 and 3 reach, the respective gates open after required time delay. Thus a closed characteristic is obtained.

The relay was designed and fabricated and its performance was found to be very satisfactory.

The salient features of this relay are:

1. The polar characteristic obtained is compatible with the fault characteristic, and is immune to power swing as blinders are used.

2. The relay is ideal for very long, heavily loaded lines,
3. The fault detection time is only one cycle.
4. The transient overreach is in limit and not more than 9 percent.
5. The relay can be designed for use with either carrier current or microwave pilot.

The drawbacks of the relay are:

1. It requires an auxillary transformer with multi-tappings and a transactor which makes it bulky.
2. Block-spike comparison may be prone to spurious signals.

2.2.4 Polyphase Distance Relay [70]:

The relays discussed in the earlier para are essentially single-phase relays. The main drawbacks of these relays are their large numbers of relay elements. In traditional system, we need three nos. of phase relays for phase faults and three numbers of ground relays for ground faults. Thus we need six relays, each having three measuring units, i.e. in all we need eighteen relay elements. In addition a fault detector is also needed. This makes the relaying scheme very bulky.

To solve this problem, switched distance relays were developed first. However, because of inherent drawbacks of this scheme, especially because of failure of switching device, polyphase relays have been developed and prefered over switched distance relays.

Most of the polyphase distance relays fails to operate on 3-phase faults or underreach for line to earth faults. Hence they require more than one decision/measuring units [68] to operate correctly on all ten types of shunt faults. Paithankar et al. [70] describe a relay which require only one measuring unit and a simple phase sequence detector responding correctly to all the ten types of shunt faults. The operating principle of the relay is described below:

Operating Principle:

Whenever a fault occurs on 3-phase system, the phase sequence of the relaying inputs S_1, S_2, S_3 and S_4 changes depending upon the type of fault. If the phase sequence can be sensed and detected, then a trip signal can be given depending upon the unwanted phase sequence which is a indication of fault.

The Fig. 2.5(a) shows the measuring circuit connected to the relay. Fig. 2.5(b) and Fig. 2.5(c) shows the sequence during normal power flow (tripping direction) and reverse power flow (non-tripping direction) respectively. The phase sequence during various types of faults is studied and it is found, that the relay (sequence detector) needs to given trip output only for the following distinct phase-sequence.

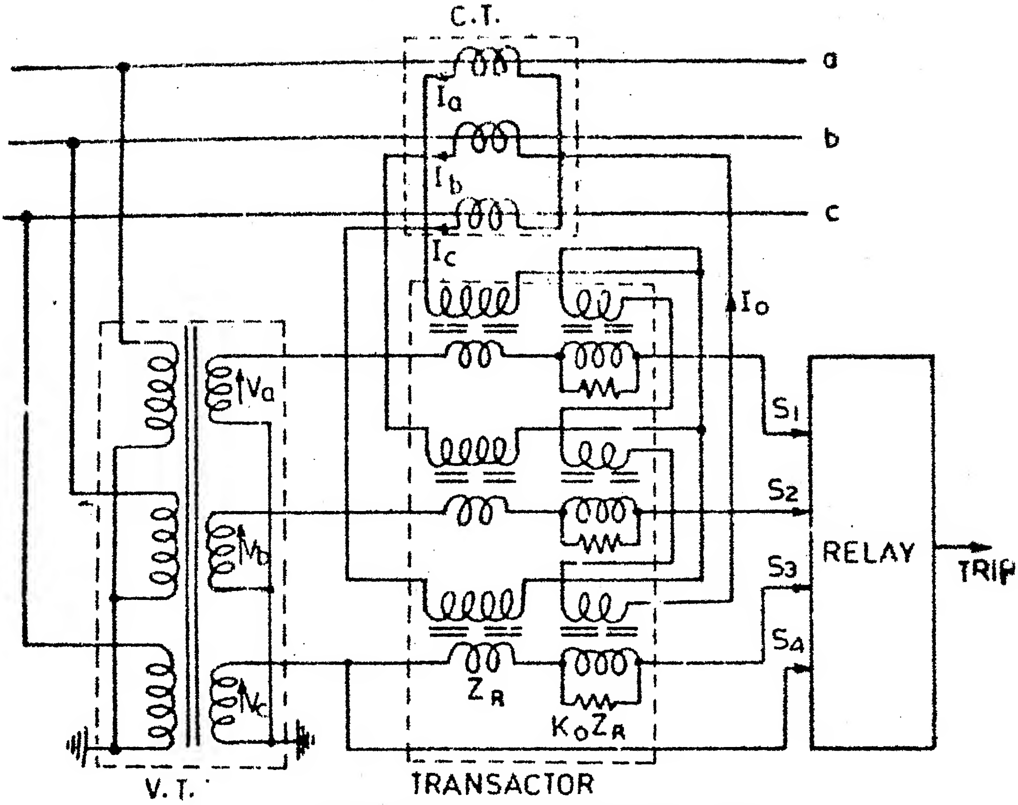


Fig. 2·5(a) RELAY CONNECTIONS

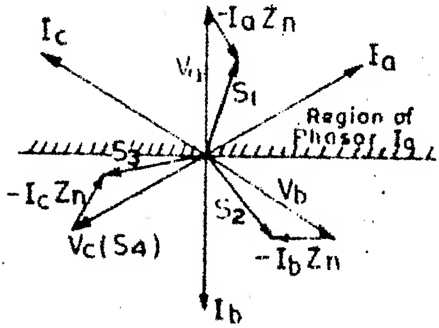


Fig. 2·5(b) FORWARD POWER FLOW SEQUENCE - $S_1|S_2|S_4|S_3$

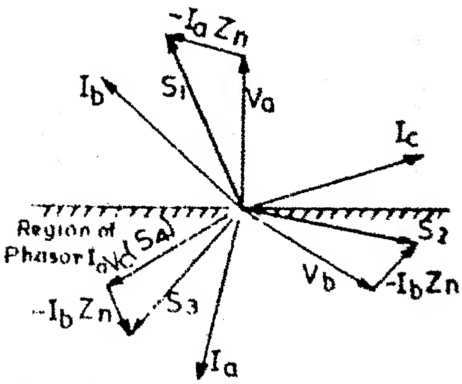


Fig. 2·5(c) REVERSE POWER FLOW SEQUENCE - $S_1|S_2|S_3|S_4$

$$\begin{aligned} &S_1/S_3/S_4/S_2 \\ &S_1/S_3/S_2/S_4 \\ &S_1/S_4/S_2/S_3 \\ &S_1/S_3/ \text{ or } S_4/S_2 \end{aligned} \tag{2.11}$$

It can be further seen that phasor S_3 or S_4 follows phasor S_1 for proper tripping, while no tripping is provided if S_2 follows S_1. This suggest a suitable pulse-sequence detector as shown in Fig. 2.6. The working of the relay is self explanatory.

The four basic relaying signals required to give proper operation for all types of faults are computed as:

$$\begin{aligned} S_1 &= V_a - (I_a + KI_o)Z_R \\ S_2 &= V_b - (I_b + KI_o)Z_R \\ S_3 &= V_c - (I_c + KI_o)Z_R \\ S_4 &= V_c \end{aligned} \tag{2.12}$$

A polyphase relay was designed and fabricated and was found to give correct tripping on all types of faults. The analysis was done by using the technique of Paithankar and Deshpande [64].

The salient features of the relay are:

1. It uses only one 4-input phase-sequence detector as a decision unit and simplifies the circuit.
2. It could be the simplest and foolproof device for all types of line shunt faults.

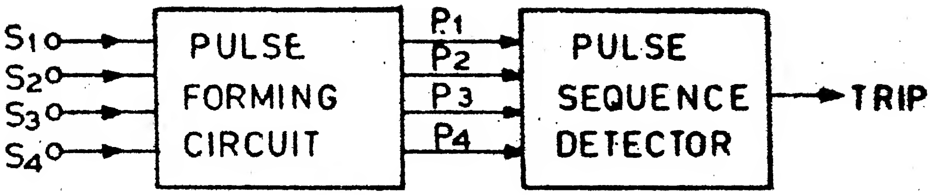


Fig.2·6(a) RELAY BLOCK DIAGRAM

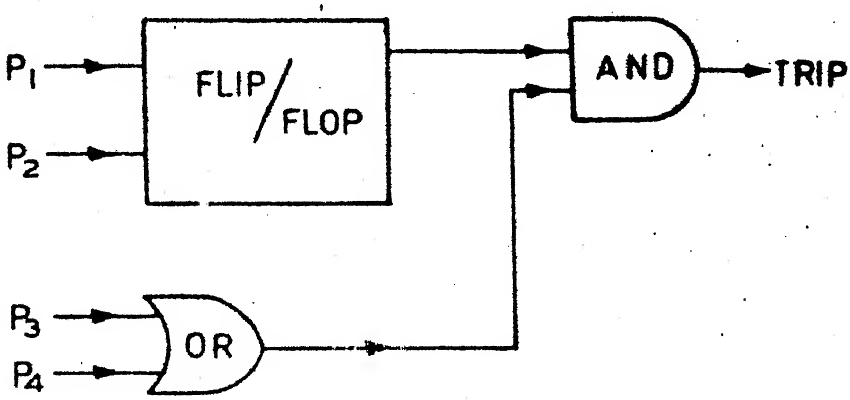


Fig.2·6(b) PULSE SEQUENCE DETECTOR

3. It gives a restraining output for sequence that correspond either to normal power flow conditions or fault outside the protected zone.

4. The relay has constant reach and is inherently directional upto $Z_s/Z_R = 22$.

5. Transient overreach for $Z_s/Z_R < 10$ is < 10 percent whereas for $Z_s/Z_R > 10$ is < 15 percent.

6. The relay can be used as back-up with the carrier or with microwave as the primary channel of protection for long lines.

Drawbacks:

1. The relay may not operate, due to high arc resistance, at the balance point as the characteristic is narrow at that point.

2. The relay may give delayed tripping due to d.c. offset component present in the post fault current.

3. The operating time can be as high as 4 cycles near the balance point due to maximum d.c. offset current and hence, not suitable for EHV lines.

4. The relay is not suited for short lines due to increase in transient overreach.

5. It is designed for single-zone operation only.

2.2.5 Polyphase Ground Distance Relaying by Phase Coincidance Principle [67]:

The earliest ground fault impedance relay was devised by Rao [19] and it works on the amplitude-comparison of fault points sequence voltages. It suffers from the defect of

having separate reach for single line to ground fault and double line to ground faults. This defect was overcome by switching arrangements in the measuring circuit which makes it rather complicated. A much simpler version was put forward by Rockfeller [40]. It gave excellent results for all single line to ground faults but was not found suitable for double line to ground faults. Bhattacharya [68] et.al. devised a polyphase distance relay, based upon 2-input phase-comparison, which could cater for all ten types of line faults but at the cost of triplication of comparators. Gupta [54] and Paithankar [70] devised polyphase relays based upon the phase sequence detection of compensated line to ground voltages of three phases. These schemes have the drawback that the tolerance to arc resistance is very marginal and the relay may maloperate due to spurious signals.

Choudhuri [67] et.al. devised a novel method for polyphase ground fault relaying with the help of simple coincidence principle of the selected input quantities. The relay works correctly on all single line and double line to ground faults and remain inoperative for all phase faults and three phase to ground faults.

Operating Principle:

A measuring circuit as shown by Fig. 2.7 is used to generate three relaying signals V_x, V_y and V_z which has a mutual

phase difference of 120° at balanced (or unfaulted) condition (Fig. 2.8). Hence, there is no coincidence between these signals. The compensated relaying signals are:

$$S_1 = V_x = V_a - (I_a+KI_{ao})\, Z_r = V_{x1}+V_{x2}+V_{xo}$$
$$S_2 = V_y = V_b - (I_b+KI_{ao})\, Z_r = \alpha^2 V_{x1}+\alpha V_{x2}+V_{xo}$$
$$S_3 = V_z = V_c - (I_c+KI_{ao})\, Z_r = \alpha V_{x1}+\alpha^2 V_{x2}+V_{xo} \qquad (2.13)$$

Now, it can be seen from the above equations that the phase sequence also remain the same at no load and at balanced load condition. During single line to ground fault on a phase, the phase sequence changes from X,Y,Z to X,Z,Y; or there is a coincidence between signals V_x, V_y, V_z. All the signals now, are within a span of 180°. It is evident from Fig. 2.9 that during a-g fault, the relay will operate so long as V_x lags V_y by $\theta_1 < 180^{\circ}$ or leads V_z by $\theta_2 < 180^{\circ}$. For a fault behind the relay, the compensated voltage never comes within a span of 180°, hence the relay is completely directional. Similar limits may also be specified during b-g and c-g faults. The tripping characteristic is as shown by Fig. 2.10 for a-g fault in forward and reverse direction. The analysis can be done on the basis of 2-input sine comparators as suggested by authors.

The complete relaying scheme is as shown by Fig. 2.11, the operation of which is self explanatory. Various steady-state

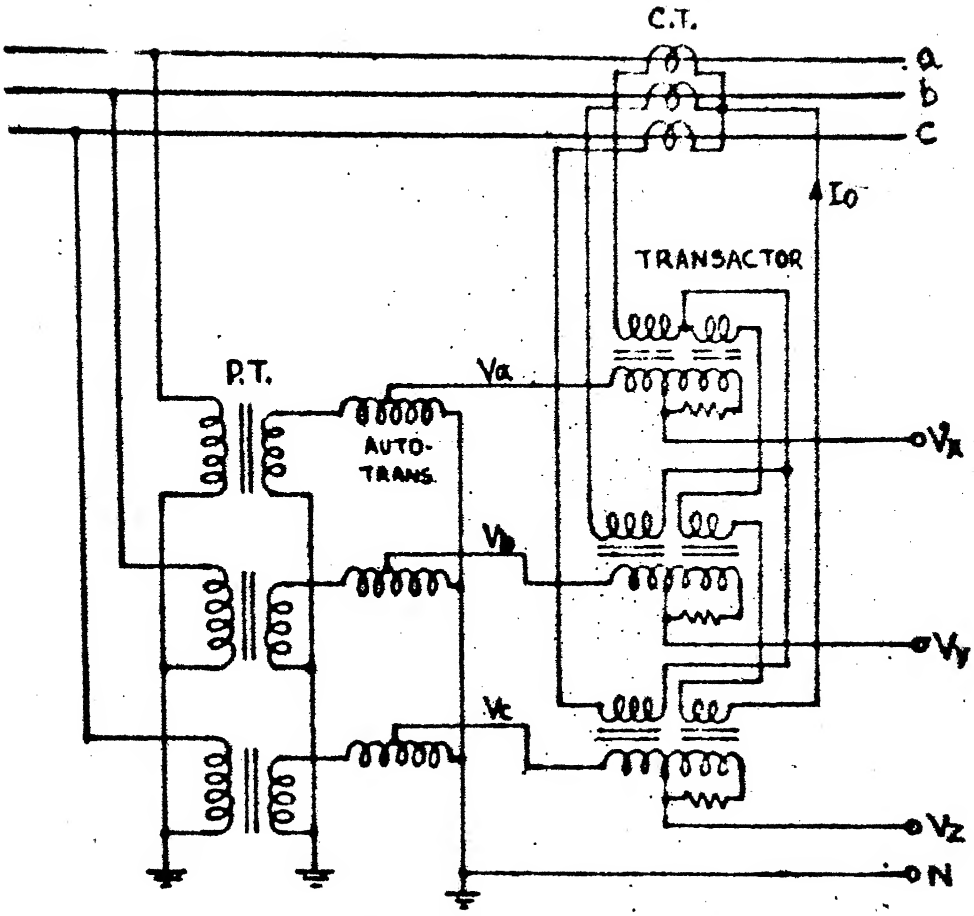


Fig. 2.7 MEASURING CIRCUIT OF THE RELAY.

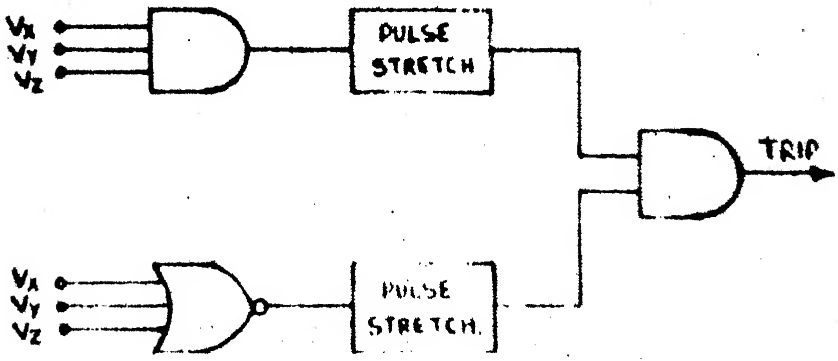


Fig. 2.11 SCHEMATIC DIAGRAM OF THE RELAY

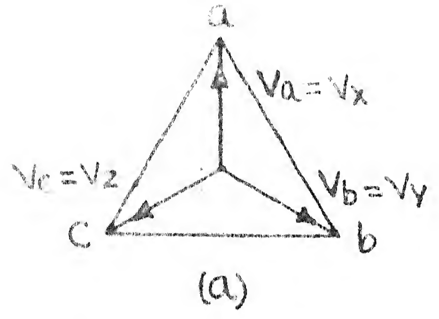


Fig. 2.8 PHASOR DIAGRAMS OF INPUT QUANTITIES
(a) NO LOAD CONDITION
(b) BALANCED LOAD CONDITION

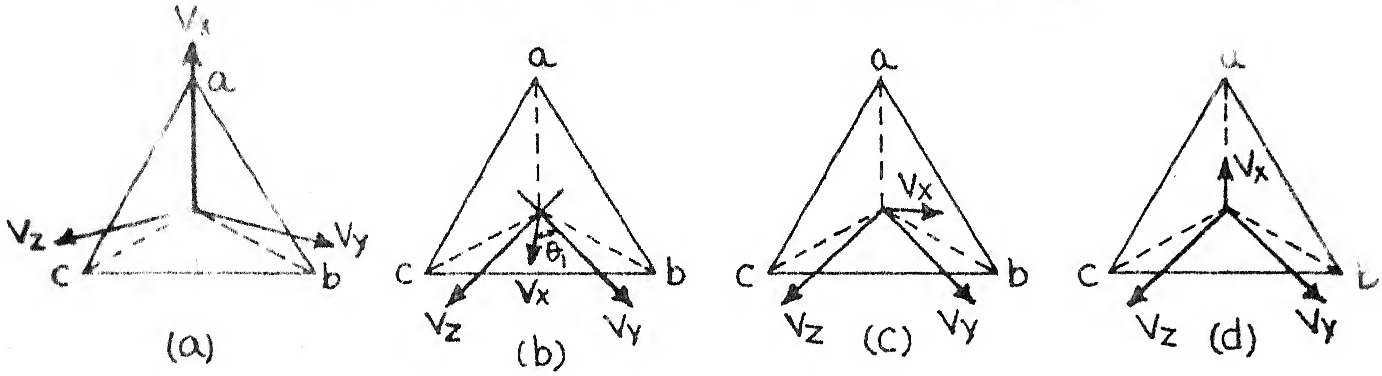


Fig. 2.9 PHASOR DIAGRAMS FOR a-g FAULT
(a) BEHIND RELAYING POINT
(b) WITHIN PROTECTED ZONE
(c) WITH ARC RESISTANCE
(d) BEYOND PROTECTED ZONE

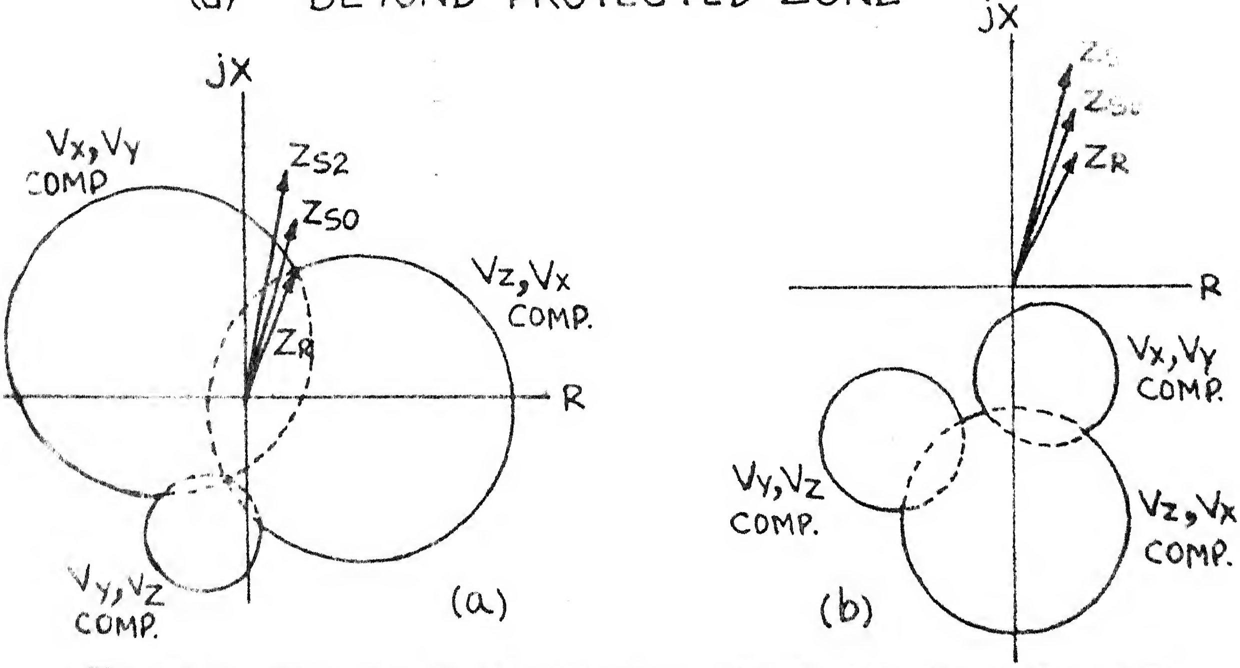


Fig. 2.10 RELAY CHARACTERISTIC ON R-X PLANE DURING SINGLE LINE TO GROUND FAULT
(a) FORWARD DIRECTION
(b) REVERSE DIRECTION

and dynamic tests were conducted and the relay was found completely stable. The salient features of the relay are:

1. Very simple and fool-proof relay circuit is devised which operates correctly for all single line and double line to ground faults but remains inoperative for double phase and 3-phase faults.
2. The relay is completely directional and is immune to balanced load and power-swing.
3. The relay has high tolerance for arc resistance and only 10% transient overreach.
4. The relay has high accuracy upto a range of 40 to 50 of the reach and a constant reach for different type of ground faults.
5. The operating time is between 18 msec to 25 msec. at any distance of fault from relay to balance point.
6. An exact equivalent circuit of relay is developed which helps in predicting the performance characteristic during different types of faults.

<u>Drawbacks</u>:

1. The relay is prone to maloperation due to spurious signals.
2. The relay is only suitable for single line and double line to ground faults.
3. The relay is designed for single-zone operation only.

Hence, there is scope for a better 3-zone polyphase relaying scheme which can cater for all types of shunts faults.

2.2.6 Versatile Digital Phase Comparator Relay [93]:

The proposed comparator, is a close digital version of analog type of block average comparison scheme, and is free from many limitations of conventional schemes. The operating time is equal to one cycle of operating frequency, anywhere within the trip region, and then, abruptly changes to infinity at the boundary of the relay characteristics. Phase angle dependent angular criterion [75] can easily be obtained which may provide greater immunity to sudden heavy loading and power swing.

Operating Principle:

In this scheme, as shown in Fig. 2.12(a), the 'conventional capacitor' is replaced by a digital up/down counter fed with constant frequency pulses. The net count, if positive (up counting) at the end of each cycle, is taken to conclude a trip condition. The digital scheme initiates a trip signal as soon as the up counting period, over one cycle, is greater than down counting period. This also resets the updown counter as shown by Fig. 2.12(b). No trip signal is initiated when up counting period is less than down counting period. The up/down ? counter is resetted at every half cycle. Hence, the relay operating time remains constant and is of one cycle duration. Asymmetrical angular comparison (criterion) can be obtained by

changing one clock frequency and counting pulses during coincidence and anticoincidence periods. Thus, characteristics made of two symmetrical arcs of circle can be obtained. Quadrilateral characteristic can be obtained by using 2-relays and applying asymmetrical angular operating criterion. The special features of this relay are:

1. The relay uses block average scheme and gives transient free operation.
2. Operating time is uniform and is of one cycle duration only.
3. No time coordination problem arises as the operating time is uniform over entire tripping area.
4. The relay is suitable for phase angle dependent variable area characteristic which prevent maloperation due to power swing and heavy overloads.
5. The relay characteristics are immune to small changes in frequencies so long as the ratio among them is maintained. This could easily be done by frequency deviders.
6. The relay seems to have excellent dynamic performance.

<u>Drawbacks</u>:

1. The TTL gates are used which are sensitive to spurious signals and hence, relay could be prone to transients and line disturbances.

2. A true polyphase relay detecting all faults may be more costlier and sophisticated than analog relay.
3. The relay performance could be greatly improved if CMOS logic or high threshold logic circuit are used in place of TTL gates.
4. It is designed for single-zone operation only

2.3 AMPLITUDE COMPARATOR:

These relays give an output signal (i.e. trip signal) when the amplitude of operating signal exceeds than that of the restraining signal by a predetermined critical value. Ideally, the output is independent of the phase difference between two relaying signals. The relay is capable of giving any type of threshold characteristics. Recent developments have shown, that these relays are more suitable for quadrilateral characteristic and also much more simpler than phase comparator relays.

2.3.1 Developments in Amplitude Comparison Techniques for Distance Relays [58]:

Most of the phase and amplitude comparators use a transactor for mixing the relaying signals which deteriorate the dynamic performance of the relay. Developments in the amplitude comparison techniques [5,8,56]have made it possible to realise different types of threshold characteristics by suitable comparison of signals derived from primary line quantities. Mclaren [48] extended this principle to a new sampling technique which allows a comparison of instantaneous values derived at

different instant of time. These schemes require more complicated circuit, and hence, author developed a simpler scheme in which relaying signals are derived from primary line quantities and instantaneous comparison of amplitudes is done at every instant of half cycle. It is, basically, a sine wave comparator, and only one measuring gate is required. Variety of pick-up characteristics can be obtained, but the technique is most suited to obtain quadrilateral characteristic. The principle of operation is as follows:

Operating Principle:

The Fig. 2.13(a) gives the block diagram of the complete relay and its characteristic is shown by Fig. 2.13(b). It can be seen that $K_1 I_L \angle\theta_1$ and $K_2 I_L \angle\theta_2$ are operating quantities whereas, $K_3 I_L \angle\theta_3$ and $K_4 I_L \angle\theta_4$ are restraining quantities. The instantaneous values of $K_1 I_L$ and $K_2 I_L$ are compared with $K_3 V_L$ continuously and judgement is made whether operating quantity is smaller or greater than restraining quantities. The relay characteristic can be represented by:

$$Z_L \leq \frac{K_1 \angle\theta_1 + K_2 \angle\theta_2}{K_3 \angle\phi+\theta_3 + K_4 \angle\phi+\theta_4} \qquad (2.14)$$

For a quadrilateral characteristic, we take $K_4 = 0$, and $\theta_3 = 0$; hence the operating quantity is $|K_1 \angle\theta_1| + |K_2 \angle\theta_2|$ and restraining quantity is $|K_3 V_L \angle\phi|$. The operation of the relay

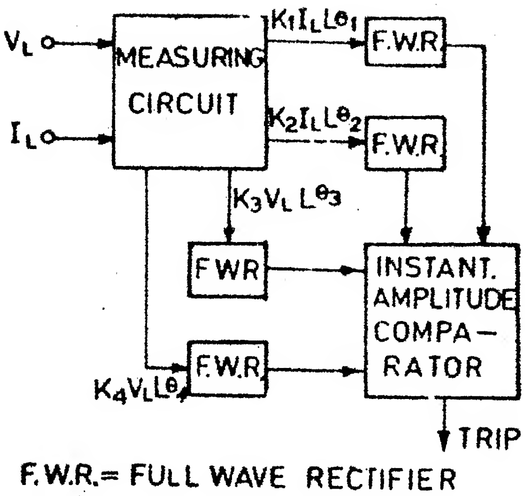


Fig.2·13(a) BLOCK DIAG. OF RELAY

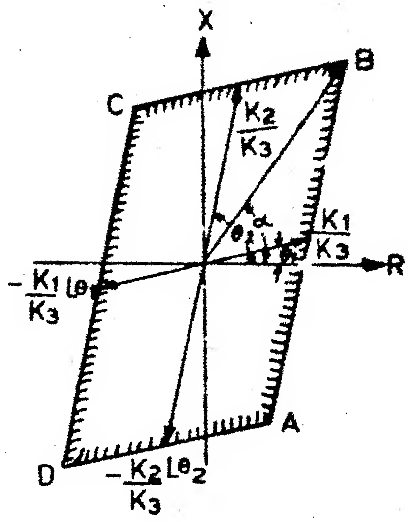


Fig.2·13(b) CHARACTERISTIC

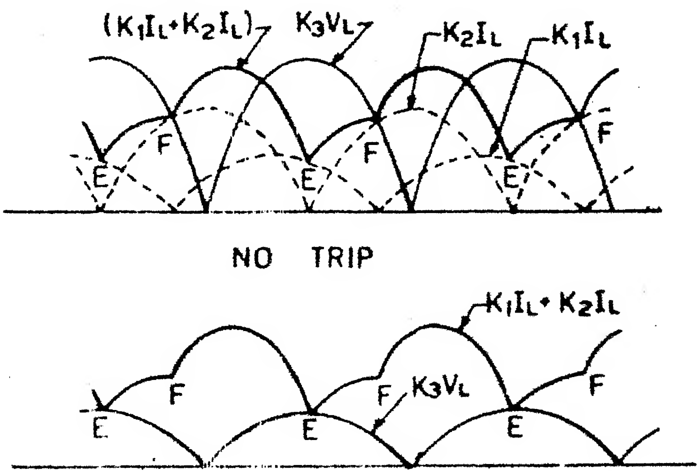


Fig.2·13(C) TRIP

is clear from the waveforms as shown by Fig. 2.13(c). Depending upon the value of the phase angle ϕ, the restraining voltage for tripping condition is limited either by point E on voltage signal $K_1I_L(K_2I_L = 0)$ or by point F on voltage signal K_2I_L $(K_1I_L = 0)$.

When $K_3\ V_L$ is limited by point E and $\theta_2 > \theta_1$, the operating criterion emerges as:

$$Z_L \leq \frac{K_1|\sin(\theta_2 - \theta_1)|}{K_3|\sin(\theta_2 - \phi)|} \tag{2.15}$$

When K_3V_L is limited by point F, the operating criterion emerges as:

$$Z_L \leq \frac{K_2|\sin(\theta_2 - \theta_1)|}{K_3|\sin(\phi_2 - \theta_1)|} \tag{2.16}$$

Equations (2.15) and (2.16) represent characteristics (lines AB and BC) which are inclined to real axis by angle θ_2 and θ_1 respectively.

Changeover of operating characteristic from line AB to BC occurs when phase angle exceeds angle α which is given by eqns. (2.15) and (2.16), i.e.

$$\tan \alpha = \frac{K_1 \sin \theta_1 + K_2 \sin \theta_2}{K_1 \cos \theta_1 + K_2 \cos \theta_2} \tag{2.17}$$

Full wave rectification of the relaying signals produces image characteristics. Hence line DC and AD are parallel to

AB and BC respectively. The characteristic can be shaped by changing θ_1 and θ_2.

The proposed relay was designed and fabricated and dynamic test results were presented which agree very well with the theoretical ones.

The salient features of this relay are:

1. No transactor is required with the result the burden is very low.
2. The scheme eliminates, zero-crossing detector, delay unit, sampling gates and amplitude pulse duration convertors.
3. Closed and improved polar characteristics with sharp discontinuities are obtained by using single measuring gates.
4. Simple mode of relay circuit and input signals.
5. The relay allows realisation of directional and over-current control.
6. The maximum over-reach during angular range of 60° to 210° is less than 10 percent.
7. Operating time for 80 percent setting is less than 1.5 cycle and near threshold, it is less than 3 cycles.

The relay has several drawbacks i.e.

1. It may not operate for close-in faults.
2. The operating time is quite large and thus it is not suitable for protection of EHV lines.
3. It is designed for single-zone operation only.

2.3.2 Multi-input Amplitude Comparator for Quadrilateral Distance Relay [80]:

This relay is based on sine-wave comparison principle and is free from maloperation due to stray pulse as reported by number of authors [43,60]. The comparator is found to generate (n-1) characteristics, if n represents the total sinusoidal inputs. The resultant characteristic is common area of (n-1) such characteristics. The operating principle of the relay is described below:

Operating Principle:

The relay operates when all operating inputs $S_2, S_3 \ldots S_n$ becomes greater than restraining input S_1. Thus suitable comparator circuit described by Fig. 2.14(a) is equivalent to (n-1), 2-input comparator with their trip contact AND compounded.

Let the inputs be:

$$\begin{aligned} S_1 &= K_1 p + K_2 q \\ S_2 &= K_3 p + K_4 q \\ S_3 &= K_5 p + K_6 q \\ S_4 &= K_7 p + K_8 q \\ S_5 &= K_9 p + K_{10} q \end{aligned} \tag{2.18}$$

Simple mathematical manipulation as reported by Mathews and Nellist [29] would lead to 4 different, 2-inputs comparator equations as shown:

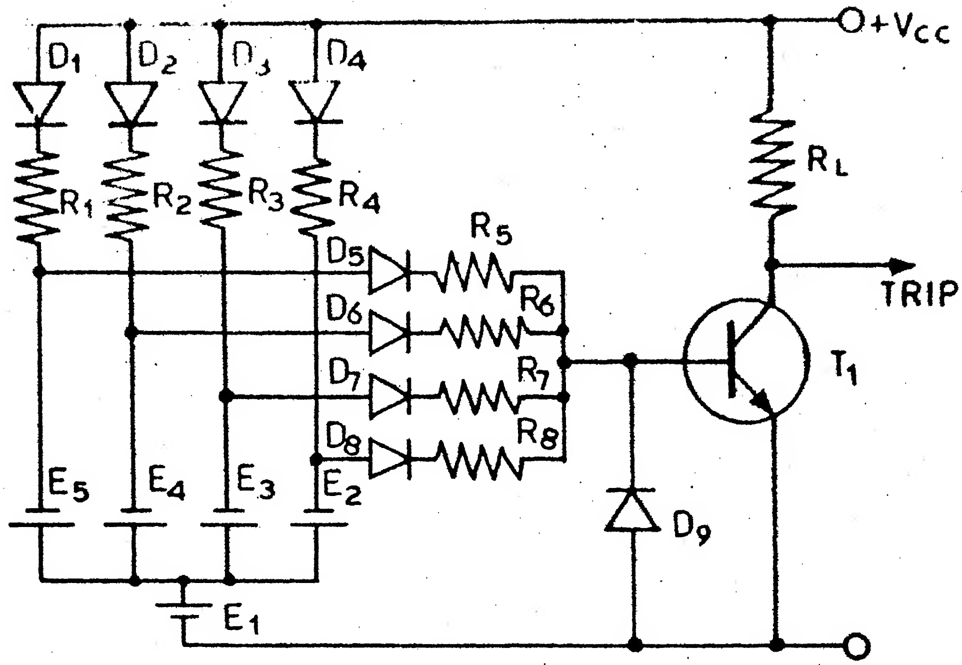


Fig.2·14(a) COMPARATOR (AND GATE)

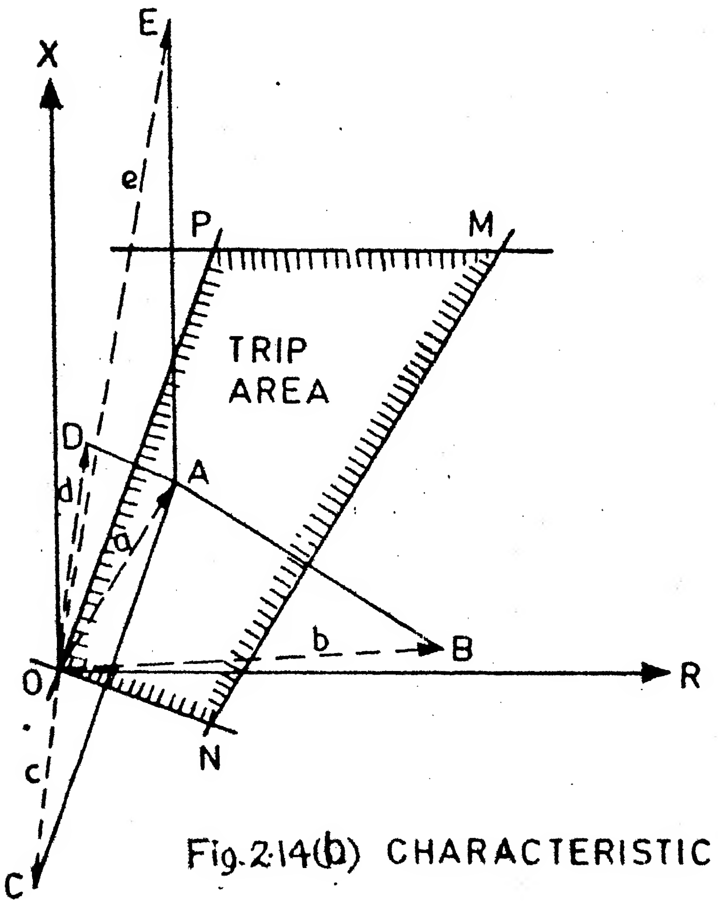


Fig.2·14(b) CHARACTERISTIC

$$\frac{w-a}{w-b} = \frac{K_3}{K_1} = r_1 \text{ for pair } S_1 \text{ and } S_2$$

$$\frac{w-a}{w-c} = \frac{K_5}{K_1} = r_2 \text{ for pair } S_1 \text{ and } S_3$$

$$\frac{w-a}{w-d} = \frac{K_7}{K_1} = r_3 \text{ for pair } S_1 \text{ and } S_4$$

$$\frac{w-a}{w-e} = \frac{K_9}{K_1} = r_4 \text{ for pair } S_1 \text{ and } S_5 \qquad (2.19)$$

Where,

$$a = \frac{-K_2}{K_1}, \quad b = \frac{-K_4}{K_3}, \quad c = \frac{-K_6}{K_5}, \quad d = \frac{-K_8}{K_7}$$

$$e = \frac{-K_{10}}{K_9} \text{ and } w = \frac{p}{q}$$

If $K_1 = K_3 = K_5 = K_7 = K_9$, then,

$$r_1 = r_2 = r_3 = r_4 = 1 \qquad (2.20)$$

Hence the equations of 4-comparators will reduce to four straight lines. These four straight lines will be perpendicular bisector of the line AB, AC, AD and AE, where points A, B, C, D and E are the extremities of vectors a, b, c, d and e respectively. The polar characteristic obtained by the above technique is shown by Fig. 2.14(b).

The condition for trip output of AND gate is:

$$E_2 \geq E_1$$
$$\text{AND } E_3 \geq E_1$$
$$\text{AND } E_4 \geq E_1$$
$$\text{AND } E_5 \geq E_1$$

The proposed relay was designed and fabricated and static tests were carried out.

The salient features of this relay are:

1. No elaborate pulse width detector is required.
2. The shape of the characteristic is fixed but independent control of any one straight line is feasible.
3. The inputs can be derived for any desired shape of quadrilateral characteristic by using graphical method and transactors.
4. The circuit is simple and it is easy to add or substract any new constraint.
5. The relay sensitivity remains constant upto $Z_S/Z_L=6.5$.
6. The operating time at 80 percent of first section is less than 10 msec. and at threshold, greater than 40 msec.

Drawbacks:

1. Many transactors can cause trouble and also delay in operation, and at the same time the relay becomes bulky and uneconomical.

2. Stray pulse may maloperate the relay as the response time is less than 10 msec. and the tripping is based upon instantaneous amplitude comparison.

3. Dynamic behaviour may be inferior compared to other schemes.
4. The VA burden is large due to many transactors.
5. The relay is not suitable for short lines as Z_S/Z_L ratio is small.
6. It is designed for zone-1 operation only.

2.4 ULTRA HIGH SPEED RELAYING (UHSR):

All the schemes discussed so far, have operating time of more than 10 msec. ($\frac{1}{2}$ cycle) and they are also not able to operate for end zone faults. The fault detection time cannot be less than 10 msec. because the measurement of fault impedance is done at steady-state conditions; i.e. when the transients are bypassed or filtered out. This is also necessary to have less transient over-reach. The stability and dynamic control of interconnected power system depends upon the speed of fault clearing. Thus the ultra high speed clearing of faults increases the transient stability and better power transfer capabilities of surplus power between large regional systems.

A new 'Ultra High Speed Relay' based upon travelling wave phenomena, which can detect and determine the fault in a few milliseconds, is proposed by a number of authors such as, Yee and Esztergalyos [90], Chamia and Liberman [91], Matele [99], Carter [101] etc. The first of this type of scheme proposed by Chamia and Leberman and installed by ASEA, Sweden

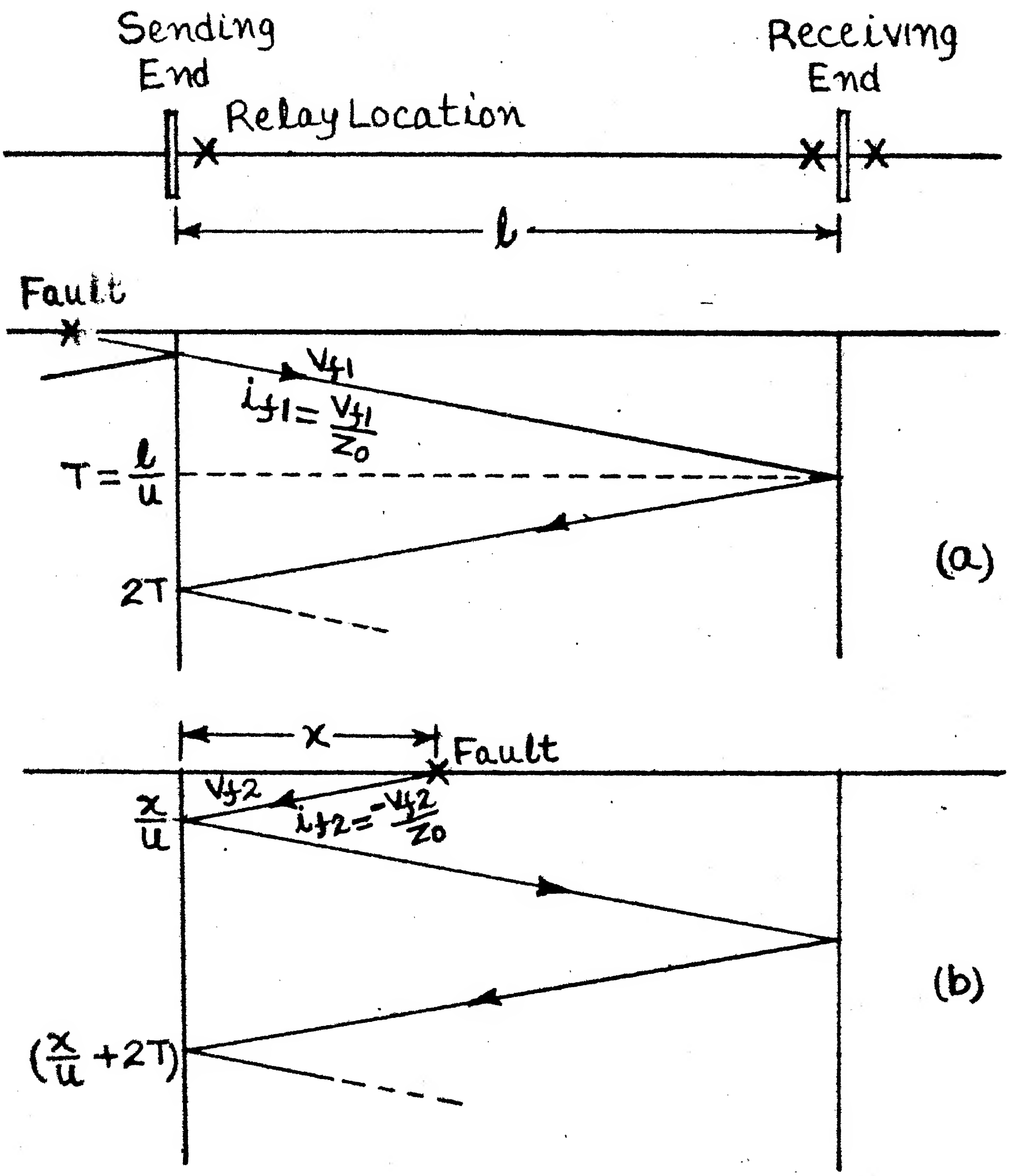
in 1976, is in use for 500 kV system in Broneville Power Administration, U.S.A. and seems to be the best of all the existing schemes.

The above scheme is, basically, a directional comparison scheme. In this scheme, the fault-generated components of the voltage and the current of the first travelling waves reaching the relaying points are used to determine the direction to the fault. These components are of opposite sign for a fault ahead of relaying point, and are of the same sign for a fault behind the relay location. Thus, only for an internal fault, they are of opposite sign at both the ends of the protected line. A recent development, proposed by Desikachar and Singh [104] is discussed in the following paragraph.

2.4.1 Operating Principle of UHSR [104].

During steady-state condition, there is no change in the line voltage and currents and thus, they have the normal values depending upon the load condition. But, during fault, transients are produced which add an additional fault generated component of voltage and current to the normal existing prefault voltage and current. Hence, we can write:

$$
\begin{aligned}
v &= v_{pf} + v_f \\
i &= i_{pf} + i_f \qquad (2.21)
\end{aligned}
$$



Lattice Diagrams For External & Internal Faults

Fig. 2.15

where v_{pf} and i_{pf} are prefault components and v_f and i_f are fault generated components of the voltage and current respectively and v and i are the voltage and current at any point of the system at any instant.

An EHV/UHV transmission line is very long and has distributed parameters and thus, the fault generated components would create travelling waves and could be tapped-off at the relay location as relaying signals. Thus, the fault will produce travelling waves; and, for a lossless line, the fault generated components are given by the well known wave equation as shown,

$$v_f = f_1(t-x/u) + f_2(t+x/u) \quad \text{and}$$

$$i_f = \frac{1}{Z_o}\,[f_1(t-x/u) - f_2(t+x/u)] \tag{2.22}$$

where, t,x,u and Z_o are time, distance from the relay location, velocity of propagation of the travelling waves and surge impedance of the line respectively and f_1 and f_2 are arbitrary functions.

It can be observed from the above equation, that $f_1(t-x/u)$ represents a forward travelling wave and $f_2(t+x/u)$, a backward travelling wave and also, that backward travelling waves of voltage and current are of opposite sign and the forward travelling waves of voltage and current are of same sign.

The relaying signals, after proper reduction of magnitudes fed to unity ratio amplitude comparator, are

$$S_1 = v_f - i_f R$$

$$S_2 = v_f + i_f R \qquad (2.23)$$

where R is a surge impedance equal to $\sqrt{L/C}$, L and C are inductance and capacitance per unit length of the line respectively.

Now, it can be observed from the Fig. 2.15(a) that, for fault behind the relay location, v_f and i_f are in the same direction, hence, by equation (2.22) and equation (2.23), $|S_1|<|S_2|$ and the relay does not operate. For a fault at distance x ahead of relay location as shown by Fig. 2.15(b), v_f and i_f are of opposite sign and hence $|S_1|>|S_2|$ which is an indication of internal fault and thus the relay operates.

For a fault at the farthest distance or near the balance point ($x = \ell$), the condition $|S_1|>|S_2|$ will be detected after a time delay of T, equal ℓ/u sec. Thus the maximum time of operation for the end zone fault would be of the order of microseconds only. If a fast microwave or carrier communication channel is used between two ends, the exchange of information can be done and thus, the relays at both the ends can operate simultaneously. The salient features of the UHSR are:

1. It is very fast in operation (< 5 msec.).
2. There is no necessity of measurement of fault impedance as only, transients are considered.
3. Saturation of C.T. and P.T. and d.c. offset in fault current does not affect the relay performance.
4. The relay is, inherently, insensitive to balanced load and power swing.
5. The relay has high accuracy, sensitivity and discrimination property for any range.
6. The relay burden is low and no time coordination is needed between the relays at the two ends.

Drawbacks:

1. The relay is highly sophisticated and may be costly also.
2. There is no point in installing such relays when the circuit breaker operating time is generally large.

2.5 CONCLUSION:

An upto date critical review of some of the important relaying schemes, intended to be used for the protection of EHV/UHV transmission lines, is done in this chapter. All these schemes suffer from one or other drawbacks; hence, there is a scope for developing a relaying scheme which is free from most of these drawbacks. Following chapters report

the design, development and testing of a digital phase-comparator and a complete relaying scheme which is simpler in circuitry, compact, reliable, economical and free from existing drawbacks. The relaying scheme is flexible, could be used both as cosine and sine comparator, suitable for single phase or polyphase with standard 3-zone of operation, giving either mho, modified mho or quadrilateral characteristic, simply by the change of input signals and using appropriate mode of operation.

A novel 3-phase relay, which is free from most of the drawbacks of the existing relaying schemes, is also proposed, designed, developed and tested. Finally a Dynamic Test Bench, to test all these relays, have been designed and fabricated.

CHAPTER 3

A GENERAL PURPOSE STATIC RELAY USING DIGITAL CIRCUITS

3.1 INTRODUCTION:

Static distance relays are commonly used for the protection of EHV/UHV transmission lines due to their high speed of operation, accuracy and reliability. Practically, no maintenance is needed once the relay is put into service except for checking VT fuse, transactor, and simulated fault clearing by relay. The relays [36,38,47] generally use analog devices which give delayed operation at threshold condition. The operating time is a function of phase displacement and becomes infinity at the boundary conditions. This creates a serious relay coordination problem [66]. This drawback was overcome by Ramamoorthy and Lal [93] by developing a comparator in which, the response time was kept constant. The authors used digital techniques and TTL logic gates (circuits). This relay was capable of generating many important characteristics such as ohms, directional, mho, restricted ohms and elliptical characteristics using variable angular criteria for operation. They also obtained a quadrilateral characteristic, based upon multi-input coincidence principle, but, rather in a different way. The digital relay appeared to be good at first sight, however a detailed study showed the following general drawbacks:

1. TTL gates used are sensitive to spurious signals due to low noise immunity, thus the relay could be prone to transients and line disturbances.

2. The basic comparator circuit appears to be more complicated, using more components, hence less reliable, and also, uneconomical and slow in operation (1 cycle to 2 cycles).

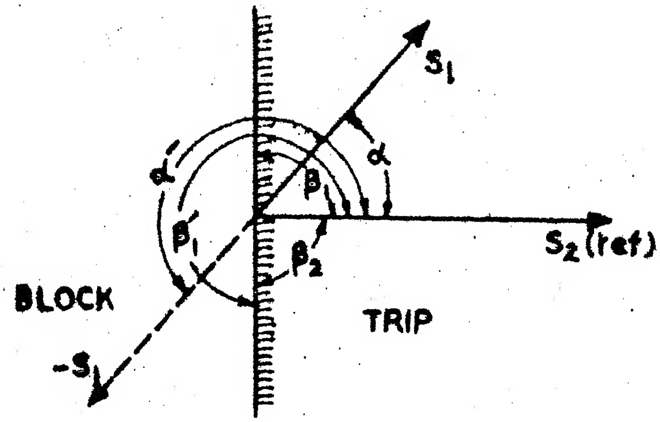
3. The same relay (comparator) can not be used to obtain quadrilateral characteristic.

4. The same comparator cannot function, both, as cosine and sine comparator.

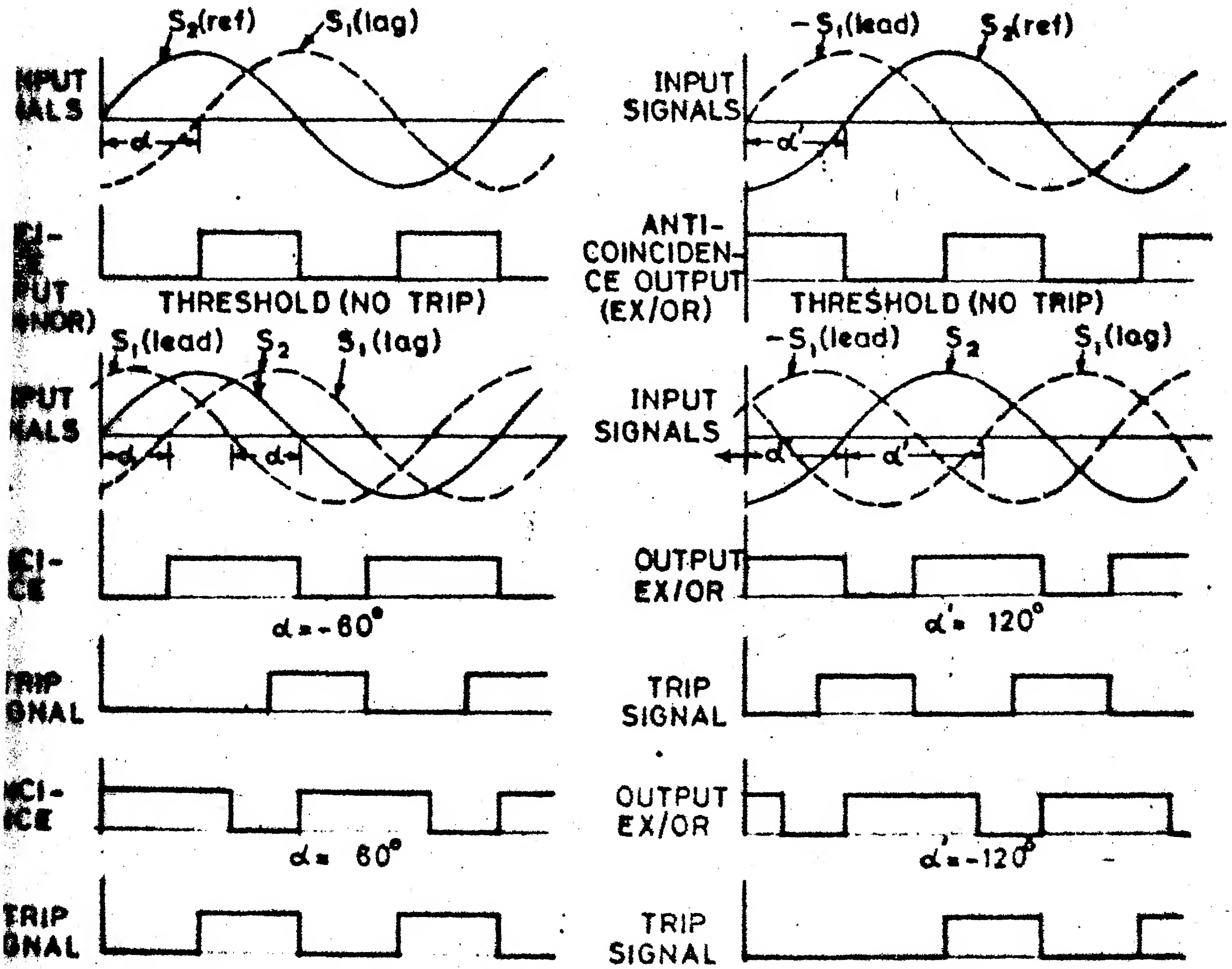
These drawbacks of existing digital relay could be elliminated by using CMOS IC's and simple relay circuit. This chapter presents the theory, design and development of an improved digital relay and technique for obtaining different types of threshold characteristics. Efforts have been made to keep the hardware to a minimum, so as to give economy and reliability with fast operating time. Flexibility is provided so that the same relay could be used, both, as cosine and sine comparator and can cater to additional requirements like power swing blocking etc.

3.2 AN IMPROVED DIGITAL COMPARATOR:

The comparator described is an Integrating Block Average type with minimum operating time of 15 milli-sec. under steady-



3.1(a) ANGULAR LIMITS & TRIPPING ZONE



3.1(b) COSINE COMPARATOR

3.1(c) SINE COMPARATOR

Fig.3.1 PRINCIPLE OF COMPARATOR

state condition and maximum operating time of 20 milli-sec. under dynamic condition. It is free from the effect of d.c. transient component appearing in the fault current and hence, this is bound to give better performance under transient condition also. Power-swing blocking can be applied through AND-gate A_3 (Fig. 3.2). The novel feature of the comparator is that it can be used as sine and cosine comparator and also as a multi-input comparator giving any desired characteristic. Apart from being used as single phase relay, with slight modifications, it can be used as a polyphase relay also thus, giving additional advantage of economy, maintenance and ease in relay coordination.

3.2.1 Operating Principle:

The two-input or multi-input phase comparator developed is symmetrical. In general, 2-input phase-comparator initiates relay tripping when the phase angle α satisfies the condition:

$$-\beta_2 \leq \alpha \leq \beta_1 \qquad (3.1)$$

The phase angle α is positive when signal S_1 leads S_2 and is negative when S_1 lags S_2. In majority of applications, the angular limit of phase comparison β_1 and β_2 are equal to $\pm 90^{\circ}$ and such comparators are called as 90° phase comparators or 'cosine-comparator'. This gives a directional characteristic,

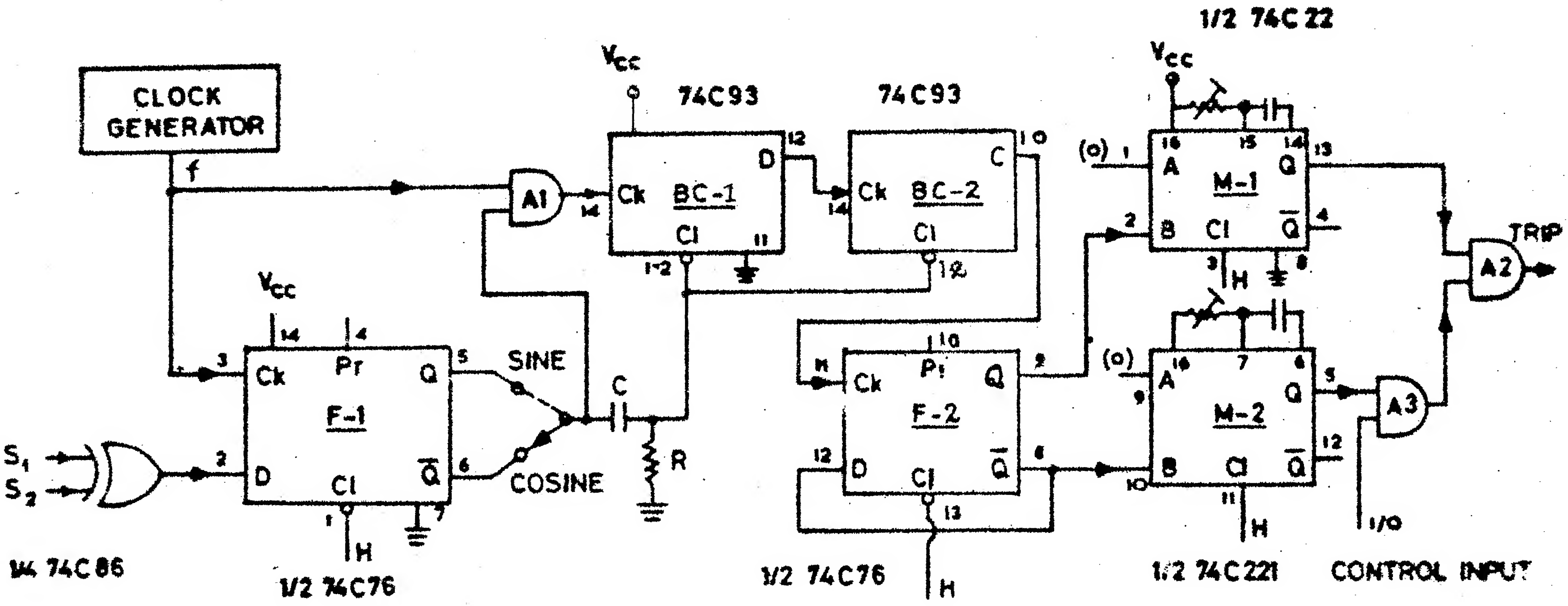


Fig.3.2 SCHEMATIC DIAGRAM OF COMPARATOR

the trip area being on right hand side for the variable signal S_1 as shown by Fig. 3.1(a). The coincidence of signals S_1 and S_2 (180-α), if more than 90°, initiates relay tripping. The tripping level is almost set equal to zero, that is why the response time is more or less the same upto $\pm 90^\circ$ of phase displacement.

The same tripping characteristics can be obtained by taking signal $-S_1$ and S_2 and measuring the anticoincidence α' between them. Tripping occurs when,

$$\beta_1' \geq \alpha' \geq \beta_1 \tag{3.2}$$

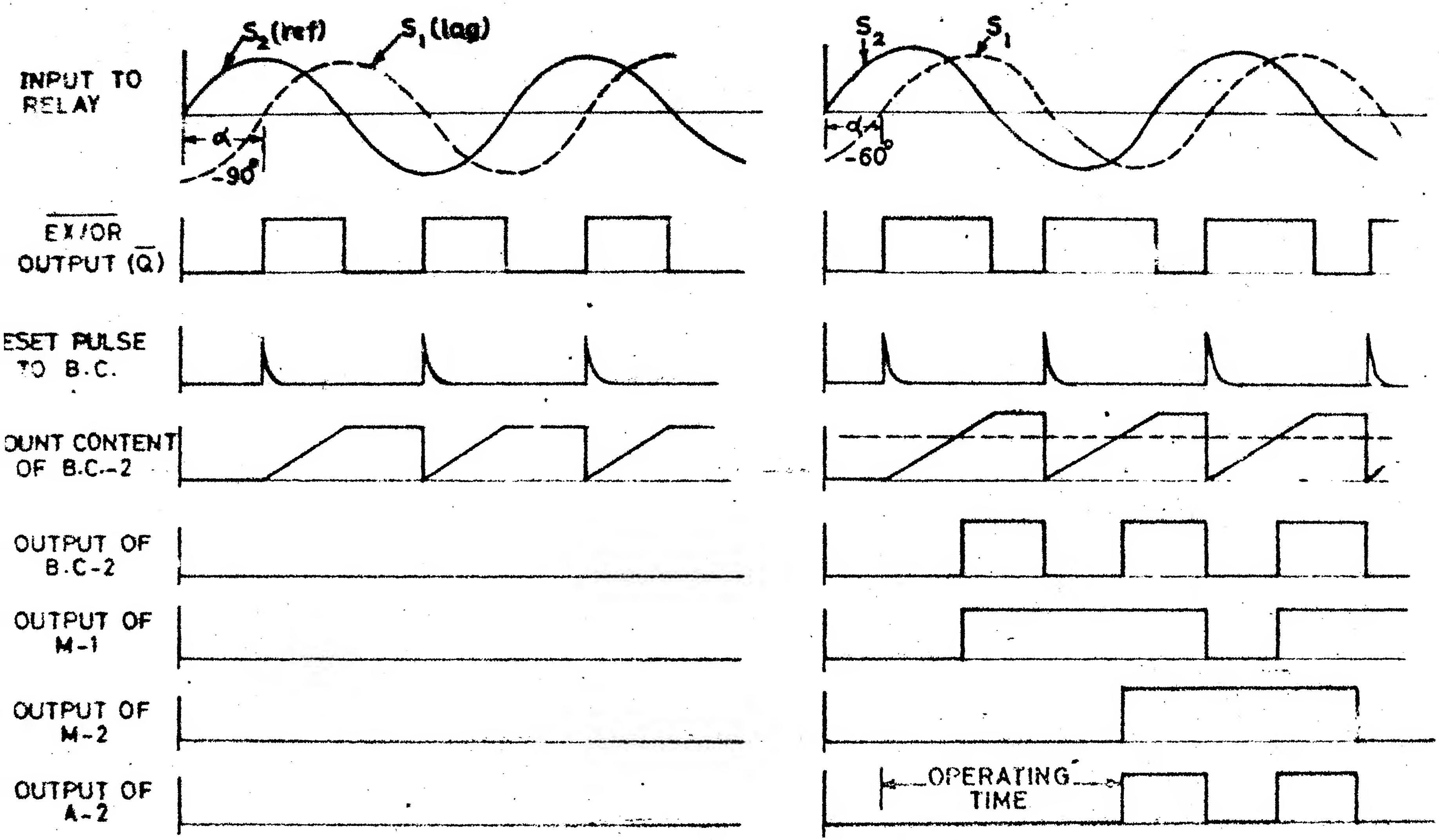
If $\beta_1 = 90^\circ$ then $\beta_1' = 270^\circ$

thus $270^\circ \geq \alpha' \geq 90^\circ$

Hence the same comparator functions as sine-comparator in which tripping occurs when $-S_1$ leads S_2 by more than 90° over a range of 0 to 180°. The waveforms are shown by Fig., 3.1(b) and (c).

3.2.2 Discription of the Comparator:

The schematic diagram of digital phase comparator is shown in Fig. 3.2. Flip-flop F-1 is used as synchronizer whereas F-2 is in 'toggle mode'. Hence, the first pulse to F-2 operates the monomulti M-1 and second pulse operates M-2 in such a way that, there exist a phase difference of 180° (10 msec. duration) between the outputs of M-1 and M-2.



3(a) COINCIDENCE = ANTICOINCIDENE (THRESHOLD CONDITION)

3(b) COINCIDENCE > ANTICOINCIDENCE (OPERTING CONDITION)

Fig.3.3 OPERATION OF COMPARATOR

Monomulti M-1 and M-2 are used as 'pulse strecher' whose outputs are 'AND compounded' by gate A-2. Thus, the operation of comparator, due to d.c. offset current, is prevented during 'threshold condition'. The AND gate A-3 is used to block the operation of relay during 'power-swing'. Normally, the control input of A-3 is set at logic (1) but becomes (0) due to the effect of 'power-swing'. Hence, the AND gate A-3 does not pass signal and thus no output from final AND gate A-2.

The sinusoidal inputs S_1 and S_2, after being converted to square pulse, are given to Exclusive-OR gate (Ex/OR). Thus the Q output of F-1 is the measure of anticoincidence (Ex/OR) where $\bar{Q}$ is the measure of coincidence (AND+NOR). The integrating capacitor is replaced by AND gate A-1 and binary counter BC-1 and BC-2. Two counters are used to increase the sensitivity of the comparator (zero level detection). The clock pulses are so chosen that 64 pulses are passed in 5 msec. duration at threshold, to give $\pm 90^{\circ}$ operating criteria. This gives the normal operating clock frequency f_o as 12.8 KHz. The variable angular criteria can be obtained by change of clock frequency. Hence,

$$\frac{f_1}{f_o} = \frac{\lambda_o}{\lambda_1} = \frac{180-\beta_o}{180-\beta_1} = \frac{90}{180-\beta_1} \qquad (3.3)$$

where,

β_o β_o = Angular criteria.

f_o = Normal operating frequency to give $\pm$ 90° criteria.

f_1 = Desired frequency to give variable operating criteria.

β_1 = Operating criteria

λ = Coincidence angle.

The above relation (eqn. (3.3)) can be used to find out new clock frequency so as to give different operating criteria β_1. Hence, the relay can generate restricted directional, restricted ohm, and a elliptical characteristics by using 2-input comparator only. The same comparator can be used as 'sine-comparator' by inverting any one input (preferably S_1) and taking Q output of flip-flop F-1. The operation of the relay as 'cosine comparator' is explained by the Fig. 3.3.

3.3 APPLICATIONS OF COMPARATOR:

The comparator can generate many important characteristics by giving suitable signals through measuring circuit. Transactors are used to simulate the line impedance. The following arrangement (Fig. 3.4) is used to obtain different signals required to produce the desired threshold characteristics.

3.3.1 Restricted Directional Relay:

The inputs to the relay to obtain directional characteristics are:

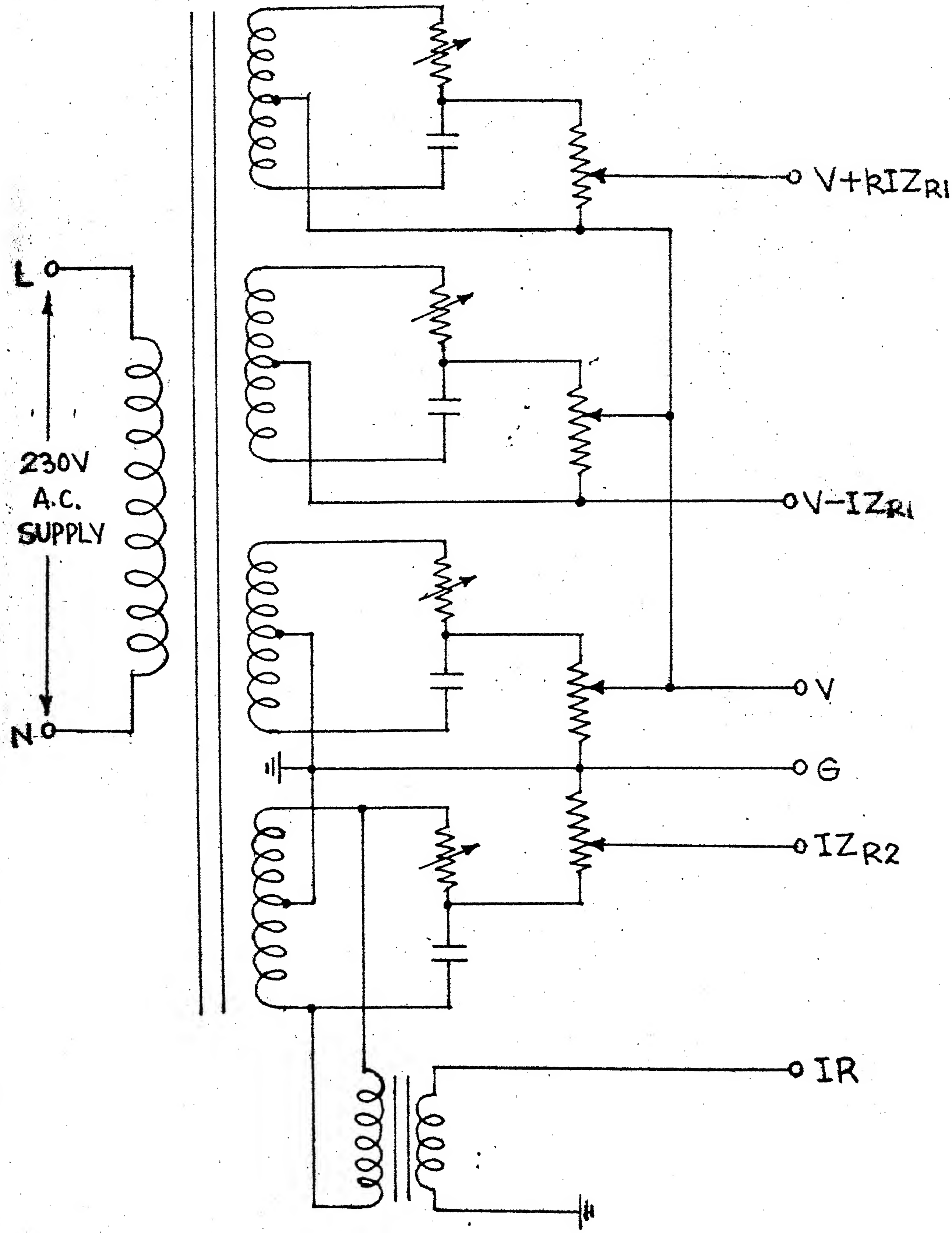


Fig. 3.4 ARRANGEMENT TO OBTAIN SIGNALS

$$S_1 = V$$
$$S_2 = IZ_R$$

This gives a straight line AOB, passing through the origin O as relay characteristic (Fig. 3.5) with normal clock frequency f_o and operating criteria of $\pm 90^{\circ}$.

Restricted directional characteristic can be obtained by the same signals, simply, by the change of the clock frequency from f_o to f_1 and f_2 in such a way that,

$$f_1 = \frac{f_o}{2-\beta_1/90}$$

and $$f_2 = \frac{f_o}{2-\beta_2/90} \qquad (3.4)$$

or

$$\beta_1 = 90(2-f_o/f_1)$$

and $$\beta_2 = 90(2-f_o/f_2) \qquad (3.5)$$

Hence, any operating criteria and threshold characteristics can be obtained by the change of clock frequency. The limits of change of clock frequency is from f_o to $f_o/2$, which is easily obtained by frequency dividers or variable potentiometer. The restricted directional characteristics are shown by Fig. 3.5 (shaded lines A'OB' and A''OB'').

If the inputs to relay are $-S_1$ and S_2, then the relay functions as 'sine comparator' with the same operating principle.

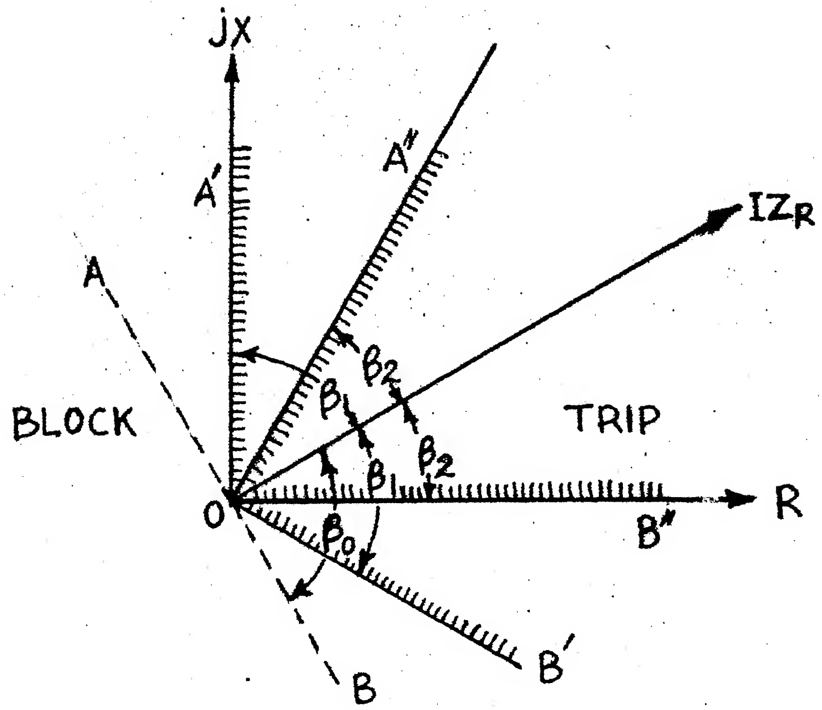


Fig. 3.5 RESTRICTED DIRECTIONAL RELAY

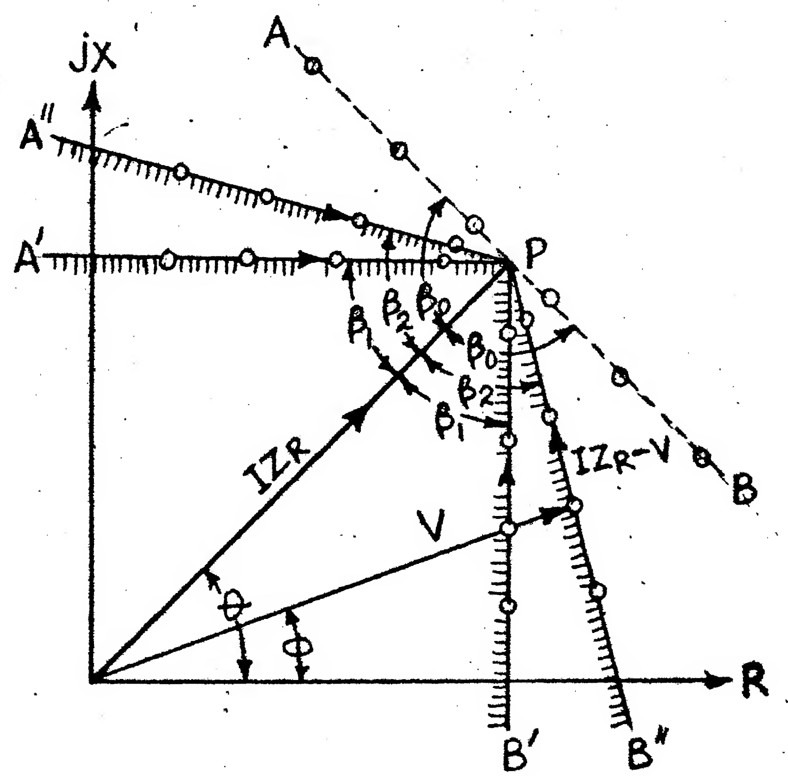


Fig. 3.6 RESTRICTED OHMS RELAY

3.3.2 Restricted Ohms Relay:

The inputs to the relay, to obtain variety of characteristics, such as ohms; i.e. angle impedance, reactance and restricted ohms are simply,

$$S_1 = IZ_R - V$$

$$\text{and} \quad S_2 = IZ_R \tag{3.6}$$

It is very interesting to note, that, characteristic APB is obtained if angular operating criteria β_o is $\pm 90^o$. If the operating criteria is β_2 and β_1 then the characteristics A''PB'' and A'PB' results. If the signal IZ_R has a phase angle of 90^o with the horizontal axis i.e. angle of the replica impedance is 90^o then, the resulting characteristic will be reactance one. Any type of characteristics can be produced by varying clock frequency in such a way that:

$$\beta_1 = 90(2-f_o/f_1),$$

$$\beta_2 = 90(2-f_o/f_2)$$

$$\text{and} \quad \beta_1 < \beta_2 < \beta_o \leq 90^o \tag{3.7}$$

The resulting characteristics are referred to as restricted OHM-characteristics. For sine comparator, the inputs to relay are:

$$S_1 = V - IZ_R$$

$$\text{and} \quad S_2 = IZ_R \tag{3.8}$$

The above theory holds good for this case also. The characteristics are shown in Fig. 3.6.

3.3.3 Mho Relay(Angle Admittance Relay):

The classical mho i.e. angle admittance characteristic can be produced by 2-input comparator with $\pm 90^{\circ}$ operating criterion, the signals being:

$$\begin{aligned} S_1 &= IZ_R - V \\ S_2 &= V \end{aligned} \tag{3.9}$$

The same characteristic can be produced by a sine comparator with signals:

$$\begin{aligned} S_1 &= V - IZ_R \\ S_2 &= V \end{aligned} \tag{3.10}$$

and $90^{\circ} \leq \beta \leq 270^{\circ}$ being the operating criterion.

It can be seen that as a sine comparator it is necessary to reverse one signal to produce the desired mho characteristic. This could be avoided in a novel way if, the signals are modified to:

$$\begin{aligned} S_1 &= V - IX \\ S_2 &= V - IR \end{aligned} \tag{3.11}$$

and $90^{\circ} \leq \beta \leq 270^{\circ}$ being the operating criteria.

The relay characteristic is shown by Fig. 3.7 which passes through the origin. It is clear that if the signal

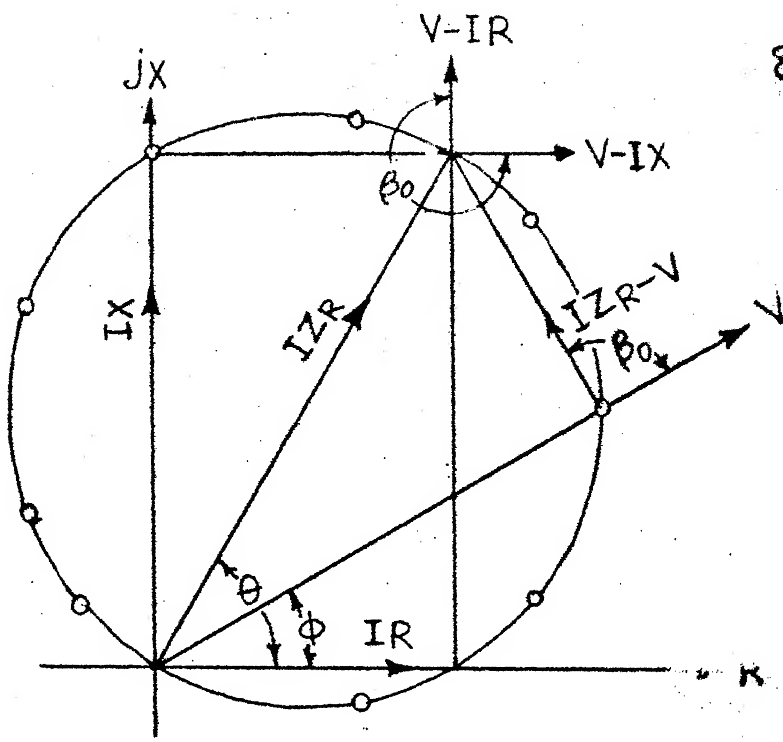


Fig. 3.7 MHO RELAY

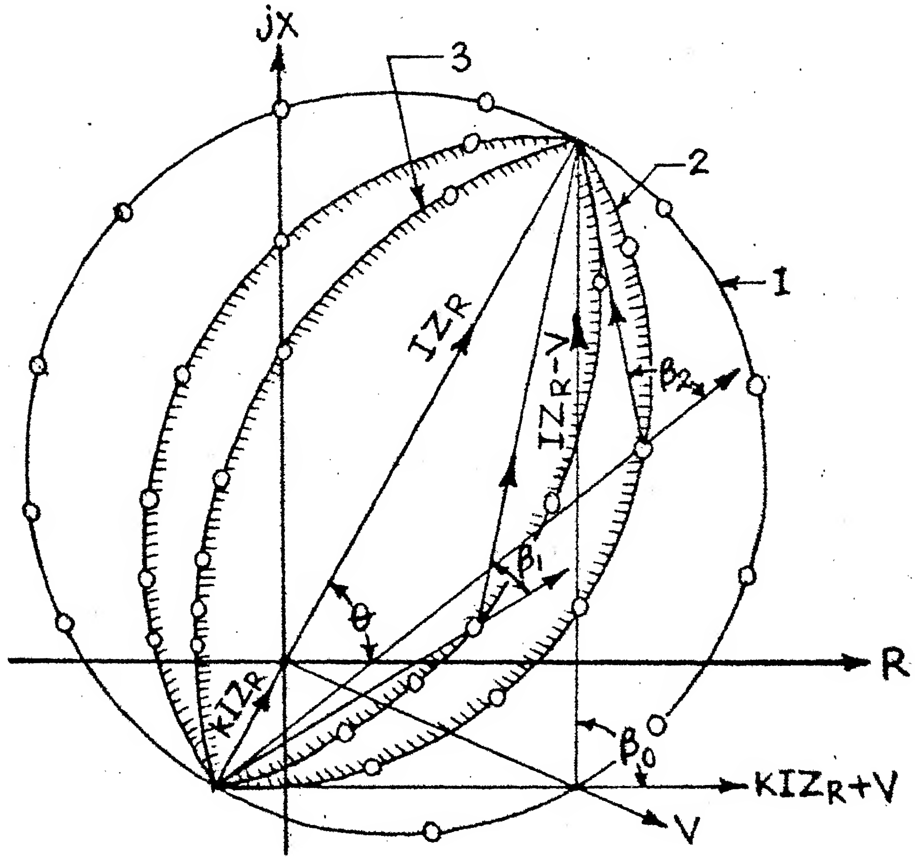


Fig. 3.8 OFFSET ELLIPTICAL RELAY

S_2 leads S_1 by more than 90°, relay operates upto a limit of 270°. Thus, the relay with these modified signals is a true sine comparator in which one signal is advanced by 90°.

3.3.4 Off-set Restricted (i.e. Elliptical) Mho's Relays:

It is the starting element for a 3-step distance relay and avoids maloperation due to power-swing. The inputs to relay are:

$$
\begin{aligned}
S_1 &= IZ_R - V \\
S_2 &= kIZ_R + V \\
k &< 1
\end{aligned}
\qquad (3.12)
$$

This can give variety of characteristics, simply, by varying the operating criteria. If the operating criteria is β_o ($\pm 90^\circ$), the resulting characteristic is offset mho as shown by curve (1) of Fig. 3.8.

The offset elliptical characteristic can be obtained by varying clock frequency from f_o to f_1 and f_2 to produce curve no. (2) and (3) of Fig. 3.8, with operating criteria as β_1 and β_2. The relation:

$$
\begin{aligned}
\beta_1 &= 90(2-f_o/f_1) \\
\beta_2 &= 90(2-f_o/f_2)
\end{aligned}
\qquad (3.13)
$$

and $\beta_1 < \beta_2 < \beta_o \leq 90^\circ$ also valid for this case.

For 'sine comparator' the inputs to the relay are:

$$S_1 = V - IZ_R$$

$$S_2 = V + kIZ_R \qquad (3.14)$$

$k < 1$ and above theory holds good for this case also.

3.3.5 Quadrilateral Relay using Two Comparators:

Fig. 3.9(a) shows the basic scheme for obtaining quadrilateral characteristic. Two comparators A and B are AND compounded to obtain the desired characteristic AOBP as shown by Fig. 3.9(b). The inputs to comparator A are:

$$S_1 = IZ_R - V$$

$$S_2 = IZ_R \qquad (3.15)$$

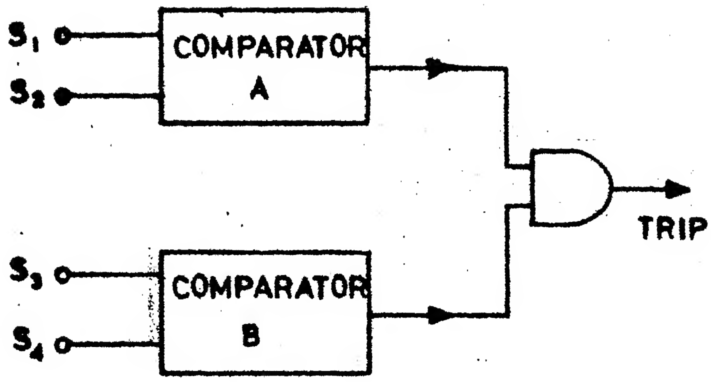
which gives restricted ohms characteristic APB with β_1 ($\beta_1 < 90^o$) as operating criteria. The input to comparator B are:

$$S_3 = IZ_R$$

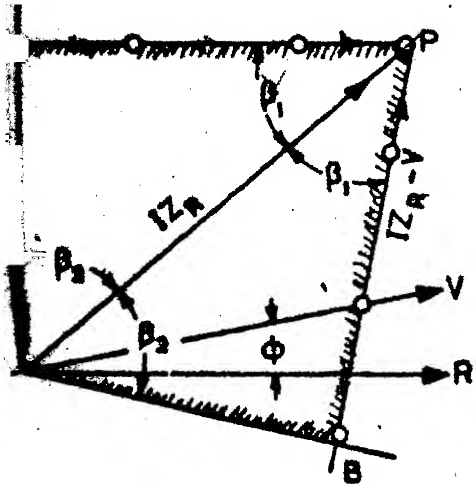
$$S_4 = V \qquad (3.16)$$

which gives restricted directional characteristic AOB with operating criteria of β_2 ($\beta_2 < 90^o$). The outputs of these comparators are, then, AND compounded to give final characteristic AOBP. By choosing appropriate value of Z_R, β_1 and β_2, better threshold characteristic with any shape can be obtained.

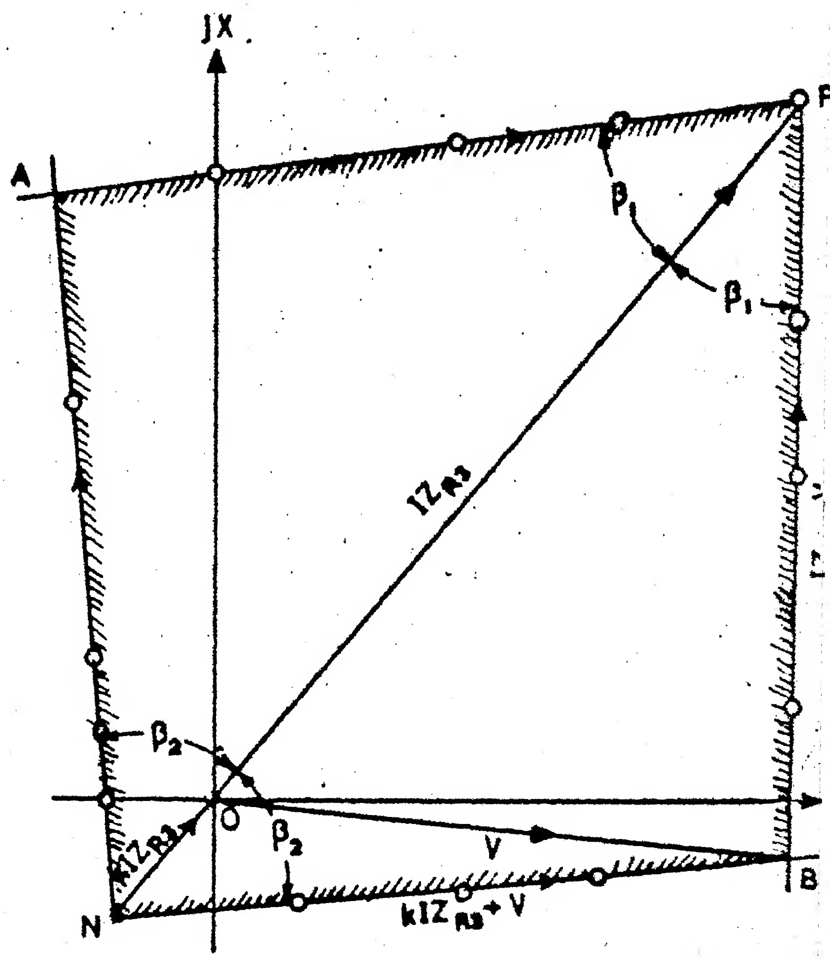
The inputs required for 'sine comparator' are:



3.9(a) MULTI-COMPARATOR RELAY



(b) NORMAL CHARACTERISTICS



3.9(c) STARTING CHARACTERISTICS

FIG. 3.9

$$S_1 = V - IZ_R$$
$$S_2 = IZ_R$$
$$S_3 = IZ_R$$
$$S_4 = -V \tag{3.17}$$

which will give same characteristics as discussed above. It can be seen that IZ_R is common to both the comparators and thus, infact only 3-inputs are needed to produce the quadrilateral characteristics.

3.3.6 Offset Quadrilateral Relay using Two Comparators:

Offset quadrilateral characteristic is required for starting element of 3-zone distance relay which can be easily obtained by modifying one of the input of comparator B hence, the input to comparator A are:

$$S_1 = IZ_{R3} - V$$
$$S_2 = IZ_{R3} \tag{3.18}$$

which gives restricted ohms characteristic APB with β_1 as operating criteria. The range of this characteristic can be changed by varying the value of Z_R so that it lies in 3rd-zone of the relay. The inputs to comparator B are:

$$S_3 = IZ_{R3}$$
$$S_4 = kIZ_{R3} + V, \text{ i.e. } IZ'_R + V,$$

which gives restricted directional characteristic ANB with β_2

as operating criteria. The output of these comparators are then, AND compounded to give the final characteristic ANBP as shown by Fig. 3.9(c). Any desired characteristic can be obtained by changing Z_R, β_1 and β_2.

The 'sine-comparator' to produce the same characteristic with the same theory of operation will have the inputs as:

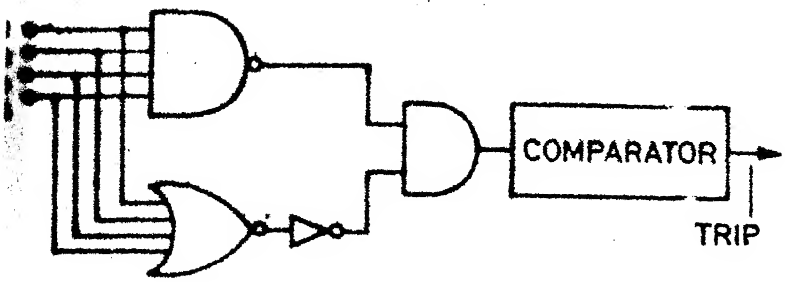
$$
\begin{aligned}
S_1 &= V-IZ_{R3} \\
S_2 &= IZ_{R3} \\
S_4 &= -(kIZ_{R3}+V) = -(IZ'_R+V)
\end{aligned}
\tag{3.19}
$$

where $Z'_R = kZ_{R3}$ and $k < 1$.

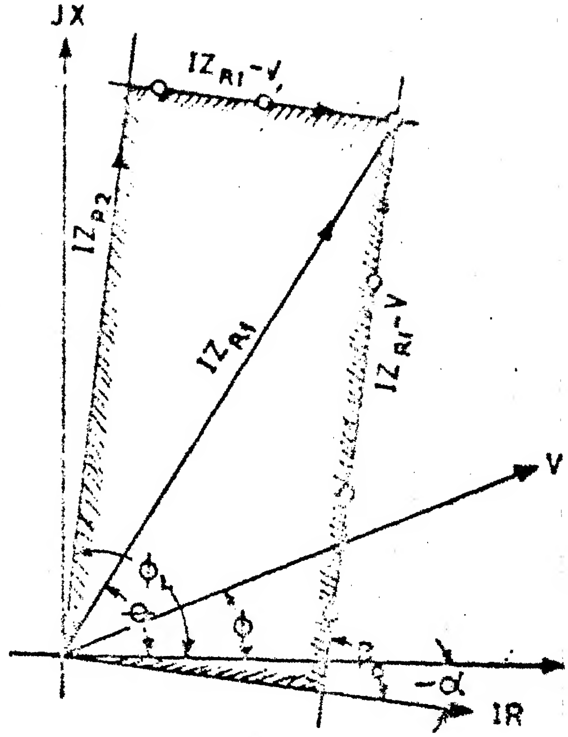
It can be seen that IZ_{R3} is common to both the comparators and hence, in fact, only 3-inputs are needed to produce quadrilateral characteristic as with cosine-comparator.

3.3.7 Quadrilateral Characteristics with Multi-input Comparator:

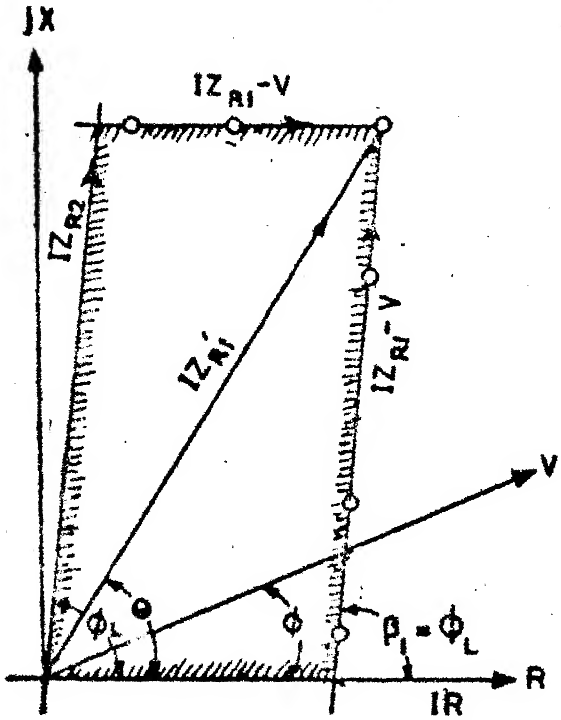
A 2-input comparator, using Ex/OR gate, can be modified to take any number of inputs, simply, by using multi-input Ex/OR gate. Four-input comparator is optimum, which can give any type of quadrilateral characteristic. As multi-input Ex/OR gate is not available, it is substituted with $\overline{\text{AND+NOR}}$ logic and rest of the circuit remains unaltered.

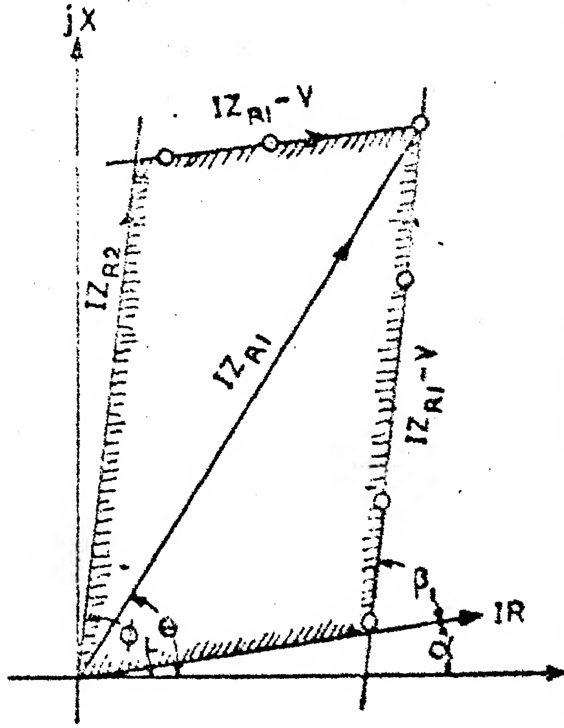


3.10 (a) MULTI-INPUT RELAY



3.10 (b) NORMAL CHARACTERISTIC





3.10 (c) MODIFIED CHARACTERISTICS 3.10 (d) SPECIAL CHARACTERISTICS

FIG 3.10

The inputs which are not used are, simply, tied up with available signals and the function of the comparator remains the same. The basic arrangement for the multi-input comparator is shown in Fig. 3.10(a).

The input signals needed for quadrilateral characteristic are:

$$
\begin{aligned}
S_1 &= IZ_{R1} - V \\
S_2 &= IR\angle{-\alpha}, \text{ (used only as a directional element)} \\
S_3 &= V \\
S_4 &= IZ_{R2}
\end{aligned}
\qquad (3.20)
$$

Z_{R2} being replica of line impedance, is used only as a directional element.

If $\alpha = 90 - \phi_L$ and operating criteria β_o is $\pm 90^\circ$, then the resulting characteristic is as shown in Fig. 3.10(b).

This characteristic can be made more compatible if the input signals to relay are:

$$
\begin{aligned}
S_1 &= IZ_{R1} - V \\
S_2 &= IR\angle{0} \\
S_3 &= V \\
S_4 &= IZ_{R2}
\end{aligned}
\qquad (3.21)
$$

Here, the angle α is set equal to zero by a 'pot' only and the operating criteria $\beta_1 = \phi_L$. This change yields the characteristic as shown by Fig. 3.10(c).

The resultant characteristic can be further modified, if the inputs to comparator are:

$$S_1 = IZ_{R1} - V$$

$$S_2 = IR \angle\alpha$$

$$S_3 = V$$

$$S_4 = IZ_{R2} \qquad (3.22)$$

The operating criteria $\beta_1 < \phi_L$ so that $\alpha = \phi_L - \beta_1$ and the resulting characteristic is as shown by Fig. 3.10(d). This characteristic may be useful for Bus-bar protection, where arc resistance is generally absent. It can be seen that by proper choice of Z_{R1} and Z_{R2}, and operating criteria β, any threshold characteristic can be obtained.

3.3.8 Modified Mho Relay:

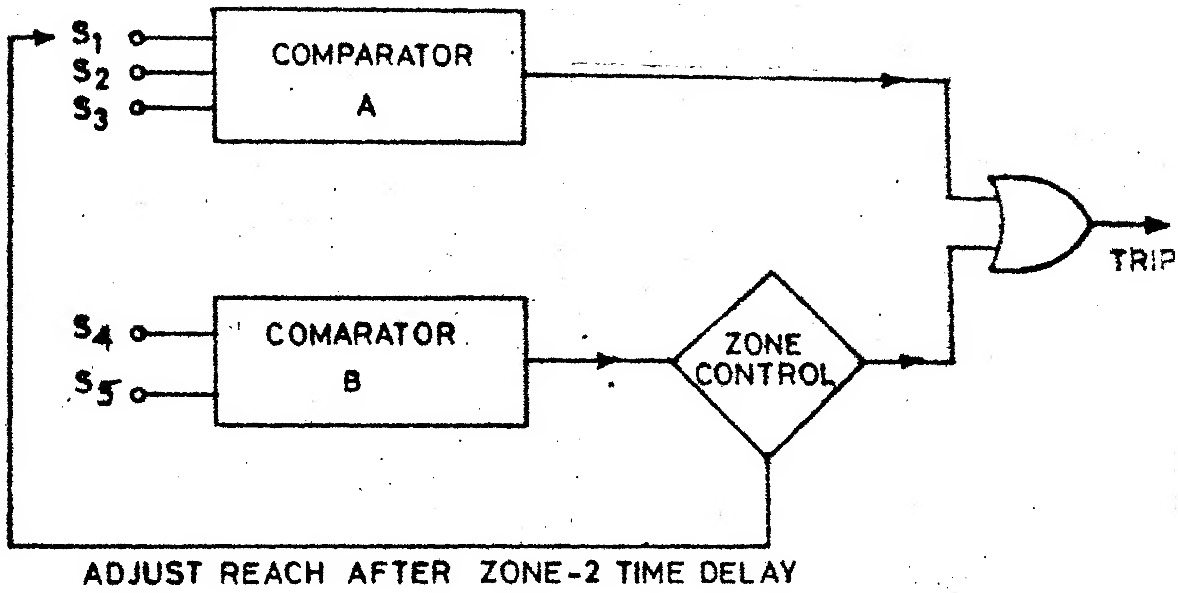
The classical mho characteristic can be modified and the effect of power-swing can be completely elliminated by using blinders and adopting suitable operating criteria β_1. Thus the inputs to the relay are:

$$S_1 = IZ_R - V$$

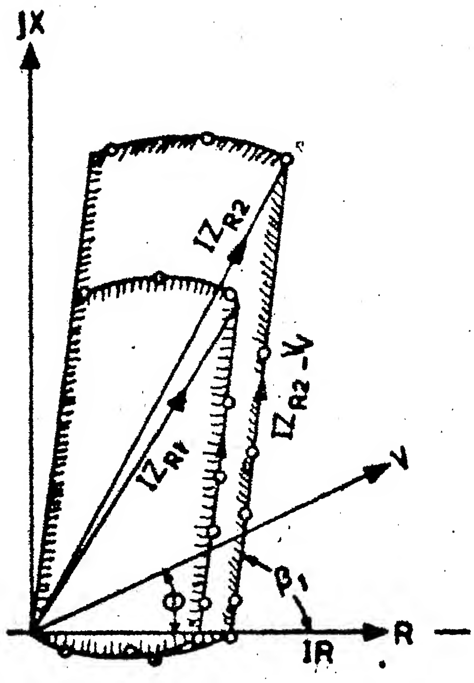
$$S_2 = IR$$

$$S_3 = V, \text{ and } \beta_1 < 90^\circ \qquad (3.23)$$

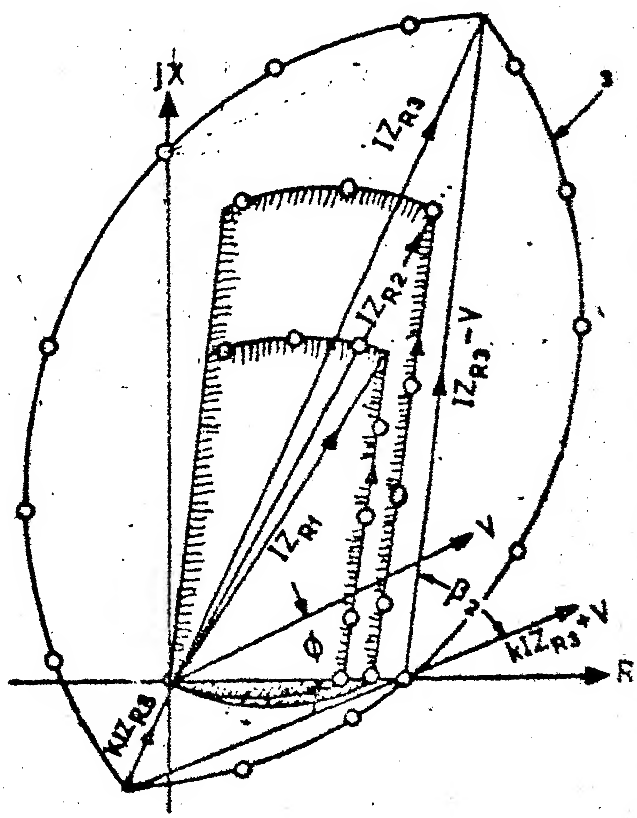
The replica impedance Z_{R1} can be changed to Z_{R2} after the zone-2 time delay, and the operating criteria β_1 is kept



3.11 (a) MODIFIED MHO RELAY



3.11 (b) CHARACT. OF COMPARATOR A



3.11 (c) FINAL CHARACTERISTICS

FIG. 3.11

equal to ϕ_L for shapping the characteristics as shown by Fig. 3.11(b). It is very interesting to note that, the resulting characteristics resembles very much like quadrilateral characteristics.

A separate comparator should be used for 3rd zone protection in a normal way, but having operating criteria as β_2 which should be less than β_1. If the inputs to this comparator are:

$$S_4 = IZ_{R3} - V$$

$$S_5 = kIZ_{R3} + V,$$

$$\text{and} \quad \beta_2 < \beta_1 < 90^\circ \qquad (3.24)$$

then the resulting characteristic is as shown by Fig. 3.11(c). It can be seen that the shape of the characteristic 3 is elliptical which is very narrow and hence immune to tripping due to power-swing. This, infact, could be an ideal starting characteristic for carrier frequency to clear end zone faults quickly by simultaneous tripping.

The block diagram of Modified Mho Relay is shown in Fig. 3.11(a).

3.4. RELAY TESTING AND PERFORMANCE:

The digital relay was tested statically due to non-availability of 'Dynamic Test Bench'. The different characteristics were plotted as shown by the respective figures. They

were found to be very close to the theoretical characteristics and hence, smooth curves are drawn passing through the test points. The directional property of quadrilateral and modified mho relay was found by reversing the signal IZ_R, which made the relay inoperative in reverse direction. The relay remains operative down to very low input voltage; but does not operate when the voltage becomes zero for 2-input comparator. However, for multi-input comparator, the relay remains operative even if the voltage becomes zero. This may be an advantage as the fault may be severe one or close-up.

3.5 CONCLUSION:

This chapter describes in detail the theory, principle of operation and applications of the Improved Digital Phase Comparator which could be used for variety of applications, especially, for the protection of EHV/UHV transmission lines. The Digital Phase Comparator is immune to, both, the d.c. offset in fault current and also to the power-swing. It can also be used as 'sine-comparator' especially in 2-input mode, giving identical characteristics as obtained by 'cosine-comparator'. The resulting relay is fast in operation and at the same time, no time-coordination problem arises as the maximum operating time is of the order of 15 msec. at the threshold condition. The

relay construction is simple, using CMOS IC's and logic gates, which makes relay economical and reliable. The same relay can produce any desired characteristic, simply by change of input signals and operating criteria. This relay could be used as polyphase relay with slight modification , giving economy and also ease in relay coordination.

Table 3.1: For Fig. 3.5 Observation for Restricted Directional Relay

$\theta = 30^{o}$, IZ = 8V, V = 8V

S.No.	$\angle \frac{V}{IZ_R}$ (degree)	Operating Critaria (degree)	Remark
1	-90		NO TRIP
2	<-90		TRIP
3	+90	$\beta_o \leq \pm 90$	NO TRIP
4	<+90		TRIP
1	-60		NO TRIP
2	<-60		TRIP
3	+60	$\beta_1 \leq \pm 60$	NO TRIP
4	<+60		TRIP
1	-30		NO TRIP
2	<-30		TRIP
3	+30	$\beta_2 \leq \pm 30$	NO TRIP
4	<+30		TRIP

Table 3.2: For Fig. 3.6 Observation for Restricted Ohms Relay

$\theta = 45^{o}$, $IZ_R = 8V$

S.No.	$\angle\frac{V}{IR}$ (degrees)	$\lvert V\rvert$ FOR TRIP $\beta_o \leq \pm 90^{o}$ (volts)	$\lvert V\rvert$ FOR TRIP $\beta_2 \leq \pm 60^{o}$ (volts)	$\lvert V\rvert$ FOR TRIP $\beta_1 \leq \pm 45^{o}$ (volts)
1	10	-	7.3	5.8
2	20	9.0	7.2	6.0
3	30	8.4	7.4	6.6
4	40	8.2	7.7	7.5
5	50	8.1	7.6	7.4
6	60	8.3	7.3	6.5
7	70	8.9	7.1	6.0
8	80	-	7.0	5.7

Table 3.3 For Fig. 3.7:

Observation for Mho Relay

$\theta = 60^{\circ}$, $IZ_R = 8V$

S.No.	$\angle \frac{V}{IR}$ (degree)	CRITICAL $\lvert V \rvert$ FOR TRIP (Volts)	OPERATING CRITARIA
1	-10	2.5	
2	10	5.2	
3	30	7.0	
4	50	7.8	
5	70	7.9	$\beta_o \leq \pm 90^{\circ}$
6	90	6.9	
7	110	5.0	
8	130	2.8	
9	140	1.2	

Table 3.4 For Fig. 3.8

Observation for Offset Elliptical Relay

$\theta = 60^\circ$, $IZ_R = 8V$, $kIZ_R = 2V$

S.No.	$\angle \frac{V}{IR}$ (degrees)	CRITICAL |V| FOR TRIP $\beta_0 \leq \pm 90^\circ$ (volts)	CRITICAL |V| FOR TRIP $\beta \leq \pm 60^\circ$ (volts)	CRITICAL |V| FOR TRIP $\beta \leq \pm 45^\circ$ (volts)
1	-50	3.0	1.8	1.2
2	-10	5.0	2.9	1.7
3	10	6.5	4.2	2.5
4	30	7.5	5.7	4.1
5	50	8.0	7.4	6.7
6	70	8.0	7.3	6.6
7	90	7.5	5.6	4.1
8	110	6.4	4.0	2.4
9	130	5.2	2.8	1.7
10	150	4.0	2.2	1.3
11	170	3.0	1.8	1.2

Table 3.5 for Fig. 3.9(b): Observation for Quadrilateral Relay

$\theta = 40^\circ$, $IZ_R = 7V$, $\beta_2 \leq \pm 55^\circ$

S.No.	$\angle\frac{V}{IR}$ (degrees)	CRITICAL $\lvert V\rvert$ FOR TRIP (volts)	OPERATING CRITARIA
1	-10	4.4	
2	10	4.8	
3	30	5.9	
4	40	6.8	$\beta_1 \leq \pm 40^\circ$
5	50	5.8	
6	70	4.7	
7	90	4.5	

Table 3.6 for Fig. 3.9(c): Observation for quadrilateral Relay

$\theta = 50$, $IZ_{R3} = 12V$, $kIZ_{R3} = 2V$,

S.No.	$\angle\frac{V}{IR}$ (degrees)	CRITICAL $\lvert V\rvert$ FOR TRIP $\beta_1 \leq \pm 40^\circ$ (volts)	CRITICAL $\lvert V\rvert$ FOR TRIP $\beta_2 \leq \pm 45^\circ$ (volts)
1	10	7.8	
2	30	8.8	
3	40	10.0	
4	50	11.8	
5	60	10.5	
6	70	9.3	
7	90	8.2	
8	110		5.6
9	130		2.5
10	150		1.8
11	180		1.5
12	-50		1.8
13	-20		3.6
14	-10		5.4

Table 3.7 for Fig. 3.10: Observation for Multi-Input Relay

$\phi_L = 85^o$, $\theta = 60^o$, $IZ_{R1}=9V$, $IZ_{R2} = IR = 8V$

S.No.	$\angle\frac{V}{IR}$ (degrees)	CRITICAL VALUE OF 'V' FOR TRIP		
		$\beta_o \leq 90^o, \angle IR = -\alpha$ (volts)	$\beta_1 \leq \phi_L$ $\angle IR=0$ (volts)	$\beta_1 \leq \phi_L - \alpha$, $\angle IR = \alpha$ (volts)
1	10	3.8	4.1	4.1
2	30	4.5	4.8	4.8
3	50	6.6	7.0	7.1
4	60	8.8	8.7	8.8
5	70	8.3	8.1	7.8
6	80	8.0	7.7	7.2

Table 3.8 for Fig. 3.11: Observation for Modified Mho Relay

$\theta_1=56^o$, $\theta_2=60^o$, $\theta_3=64^o$, $IZ_{R1}=5.5V$, $IZ_{R2}=7.5V$, $IZ_{R3} = 10V$

S.No.	$\angle\frac{V}{IR}$ (degrees)	CRITICAL VALUE OF 'V' FOR TRIP FOR		
		$IZ_{R1}, \beta_1 \leq 84^o$	$IZ_{R2}, \beta_1 \leq 84^o$	$IZ_{R3}, \beta_2 \leq 60^o$
1	-50	-	-	1.5
2	-10	-	-	2.5
3	0	2.3	2.7	3.2
4	20	2.7	3.1	5.0
5	40	3.5	4.0	7.3
6	50	4.4	5.2	8.5
7	60	5.2	7.2	9.5
8	70	5.0	7.1	9.4
9	80	4.5	6.5	8.3
10	90	-	-	7.1
11	110	-	-	4.8
12	130	-	-	3.0
13	170	-	-	1.6

CHAPTER 4

A POLYPHASE 3-ZONE DISTANCE RELAY USING DIGITAL CIRCUITS

4.1 INTRODUCTION:

The polyphase distance relays are generally used for the protection of EHV/UHV transmission lines, and they are of three types. The first type respond to all kinds of ground faults [19,40,67], the second respond to all kinds of phase faults [17], and the third, respond to all types of shunt faults [54,68,70]. A measuring unit is used in all tne above schemes which provide a compensated line to ground fault point voltages to the comparators. The earliest ground distance relaying scheme derived by Rao [19], works on the principle of amplitude comparison of fault point sequence voltages. It suffers from the defect of having separate reach for single line to ground fault and double line to ground fault. This defect was overcome by switching arrangement in the measuring circuit, which make it rather complicated. A much simpler version was put forward by Rockfeller [40]. It gave excellent performance for all single line to ground faults but it was not suitable for double line to ground faults. These drawbacks were overcome by Chaudhury [67] et.al. by developing a ground distance relay which works on the principle of phase coincidence of selected input quantities. This is perhaps the most simple and reliable relay

for all kinds of faults except for 3-phase to ground fault. Sonneman [17] devised a phase-relay which is a polarised mho relay and works on the principle of phase comparison between selected input signals using 180° sine comparators. A polyphase relay, clearing all ten types of line faults was devised by Bhattacharya [68] et.al. It works on the principle of 2-input phase comparison using 180° sine comparators. A quadrupulation of 2-input comparators with their trip output OR gated gives the final relaying scheme. It has one drawback, viz., 90° cos comparators are converted to 180° sine comparators by phase-shifting transformers and hence, can cause delay in tripping, specially, if the fault takes place near the balance point. Gupta [54] and Paithankar [70], Basu [81] and Patra [82] devised a true polyphase relay based upon the phase sequence detection of 3 to 4 compensated line to ground voltages. The main drawbacks in these schemes are, very marginal tolerance to arc resistance and malfunction due to spurious signals.

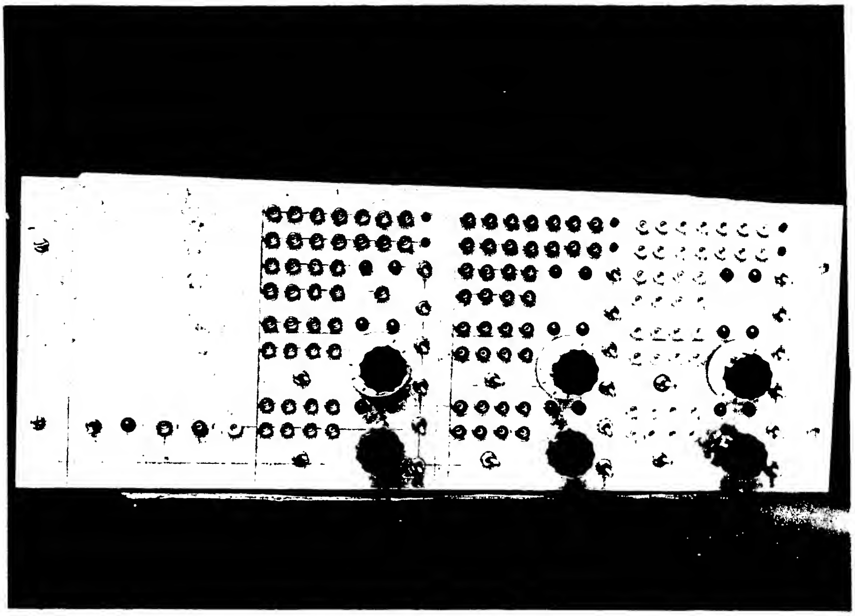
The protection schemes for EHV/UHV transmission lines are quite complex. The modern trend is to use static relays with operating time of less than one cycle (20 msec.). The stability and dynamic control of interconnected power systems, to a very great extend, depends upon the speed of fault clearing. As a matter of fact, the high speed clearing of fault

increases the transient stability. Hence, for the protection of such EHV/UHV transmission lines, an efficient, reliable, fast operating and compact relaying scheme is needed.

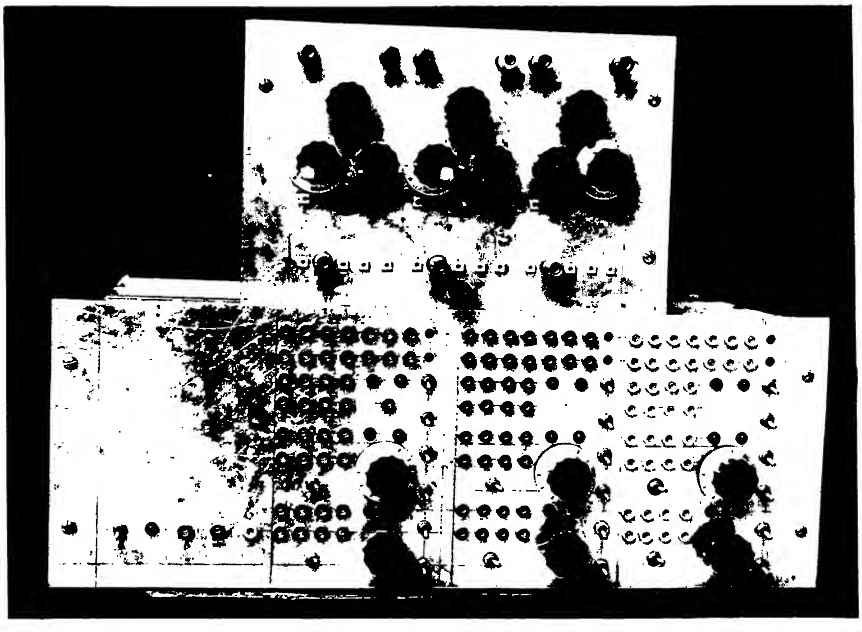
This chapter deals with a new relaying scheme using 'CMOS' logics and digital IC's, which does not use a separate starting and electromechanical unit for zone changing. The proposed polyphase distance relay is based upon the techniques used in Versatile Phase Comparator [93]. The proposed relay uses three transient free 90° cos comparators with constant operating time of 15 msec. for a fault at any distance upto the balance point. Suitable inputs are provided to these comparators, via measuring circuit, in such a way that, the polyphase relay respond to all types of shunt faults.

4.2 PROPOSED RELAYING SCHEME-I (CLASSICAL CHARACTERISTIC) BY USE OF 2-INPUT COMPARATORS:

The Fig. 4.1 shows the block diagram of polyphase distance relaying scheme. Here, the output of phase module (A), (B) and (C) are OR gated to give a final trip signal. The phase module (A), (B) and (C) are in fact, single phase relays, the principle of operation of which is based upon 2-input digital phase comparators. The present relaying scheme can give classical mho characteristic in zone-1 and zone-2, and an elliptical characteristic in zone-3 by the use of 2-inputs only. It can also give modified (restricted) mho



POLYPHASE 3-ZONE DISTANCE RELAY



DISTANCE RELAY WITH TRANSACTOR

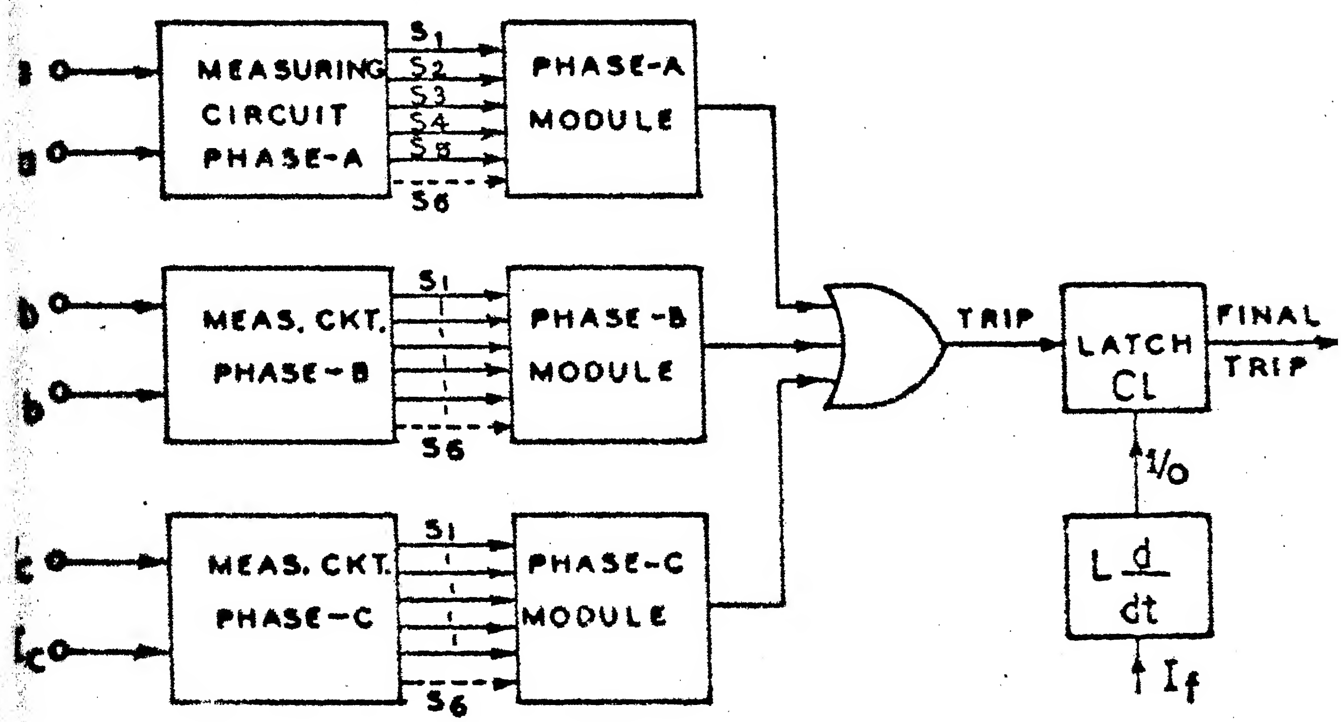


Fig 4.1 POLYPHASE 3-ZONE DISTANCE RELAY

characteristic with blinders or a quadrilateral characteristic, by the use of 3-inputs only, for all the 3-zones. The later characteristics are possible by the use of multi-input digital phase comparator. Thus, the relaying scheme is flexible one and can be used in any situation to provide any desired characteristic. As each phase module is the heart of the relay, it will be desirable to describe the working of it in detail.

4.2.1 An Improved Phase Module (Comparator):

Fig. 4.2 gives the block schematic diagram of each phase module. It can be seen that, the comparator-1 handles zone-1 and zone-2 whereas comparator-2 handles zone-3 only. Both these comparators are independent and hence, they give trip signal at the output of digital integrater, every half cycle if the fault lies in zone-3 and zone-2. The lower comparator passes this trip signal to OR gate after a time-delay t_3 (> 200 msec) and the upper comparator passes this trip signal after a time-delay t_2 (> 100 msec). Now, if the fault happens to be in zone-1 also, the reach of the upper comparator changes from zone-2 to zone-1 and the time delay t_2 vanishes via 'zone detector and timer control'. Now, the trip signal is available at OR gate after a time-delay of t_1 (>10 msec) via 'pulse stretcher with transient block control'. Hence, the 1st trip signal to circuit breaker is given within 15 sec. and then after every 10 msec. If, by chance, the restraining

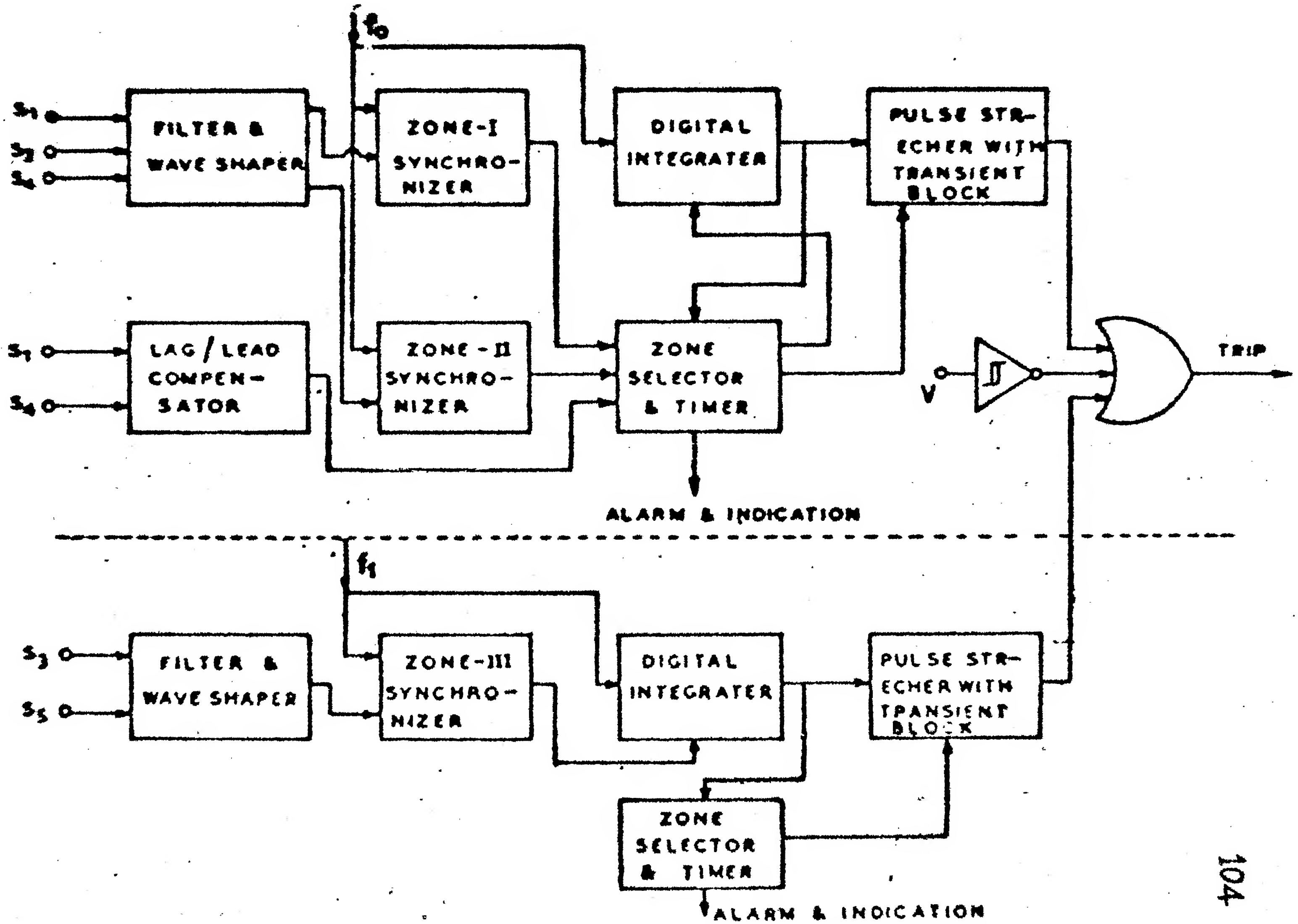


Fig.4.2 BLOCK DIAGRAM OF 3-ZONE DISTANCE RELAY (PHASE MODULE)

voltage (V) vanishes, then OR gate issues an instantaneous trip signal (< 5 msec.) which is desirable as the fault may be a severe or close-up one. The comparators used are of 2-input, block average 90^{o} coincidence digital phase comparator which have a constant operating time of 15 msec. for fault at any distance upto the balance point.

4.2.2 Operation of 3-Zone Phase Module:

Fig. 4.3 gives the simplified circuit diagram of 1-phase relay using digital components. In general, the signals to upper comparator to give mho characteristic are:

$$S_1 = IZ_{R1} - V \quad \text{For zone-1 operation}$$

$$S_4 = V \qquad (4.1)$$

and,

$$S_2 = IZ_{R2} - V \quad \text{for zone-2 operation}$$

$$S_4 = V \qquad (4.2)$$

Cosine comparators are used, as the operating critaria is $-90^{o} < \beta < 90^{o}$. Flip-flops (B-1 and B-2) act as zone synchronizer with clock frequency (f_o) to give $\pm 90^{o}$ of operation. The digital integration is done by Binary Counter (BC-1 and BC-2) over a period of 5 msec ($\frac{1}{4}$ cycle), thus the frequency (f_o) is taken to equal to be 12.8 KHz. If the fault lies in zone-2, the output of B-2 is connected to digital integrator (BC-1 and BC-2) which gives a pulse after 5 msec and operates a

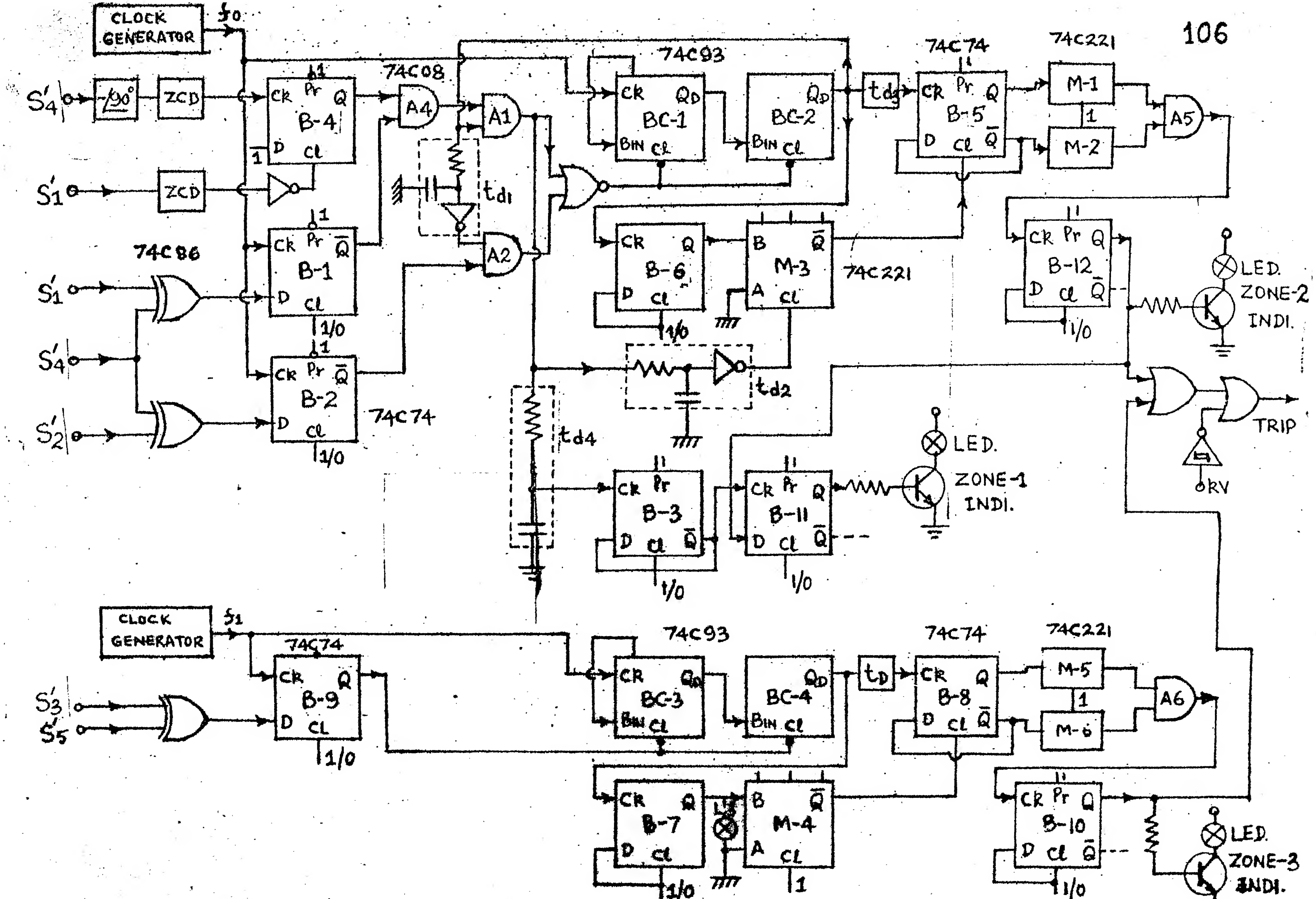


Fig.4.3 SCHEMATIC DIAGRAM OF 3-ZONE DISTANCE RELAY

monostable (M-3) through flip-flop (B-6). Thus, the $\bar{Q}$ output of M-3 goes to logic (0) and resets B-5 hence, B-5 does not pass the pulse as it comes after time delay (t_{d3}). The M-3 resets after the zone-2 time delay (t_2) and thus, B-5 passes one pulse for every two input pulses. The output of M-1 and M-2 has a time lag of 10 msec and duration of 15 msec. Thus, the output of A-5 is a regular pulse of 5 msec. duration at an interval of 10 msec. These pulses operate a latch B-12 which gives the indication of zone-2 operation and a trip signal through OR gate (01 and 02).

If the fault happens to take place in zone-1 also, A-1 sends a pulse along with BC-2 and sets M-3 to logic (1) once again hence, zone-2 time delay (t_2) is elliminated, enabling B-12 to issue trip signal with zone-1 time delay (15 msec), and trip indication by B-11 through B-3. The signal to lower comparator for 3rd-zone operation are:

$$S_3 = IZ_{R3} - V$$
$$S_5 = kIZ_{R3} + V \qquad (4.3)$$

with clock frequency (f_o) which gives offset mho circular characteristic normally required for starting elements. If the fault lies in zone-3, the upper comparator remains inoperative, but the lower comparator gives a trip pulse after a time delay of t_3 sec. due to B-7 and M-4. The BC-4 gives a trip

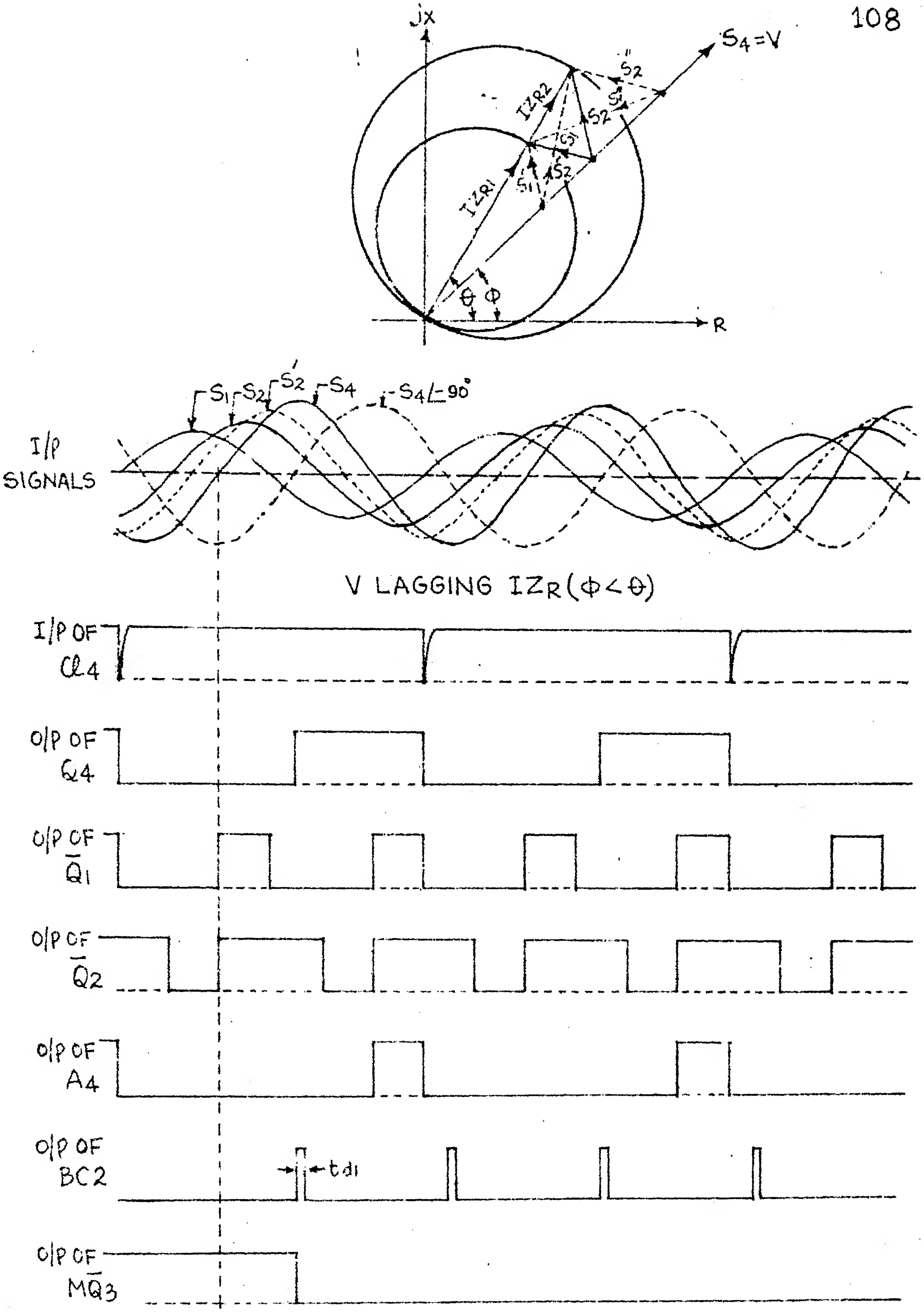
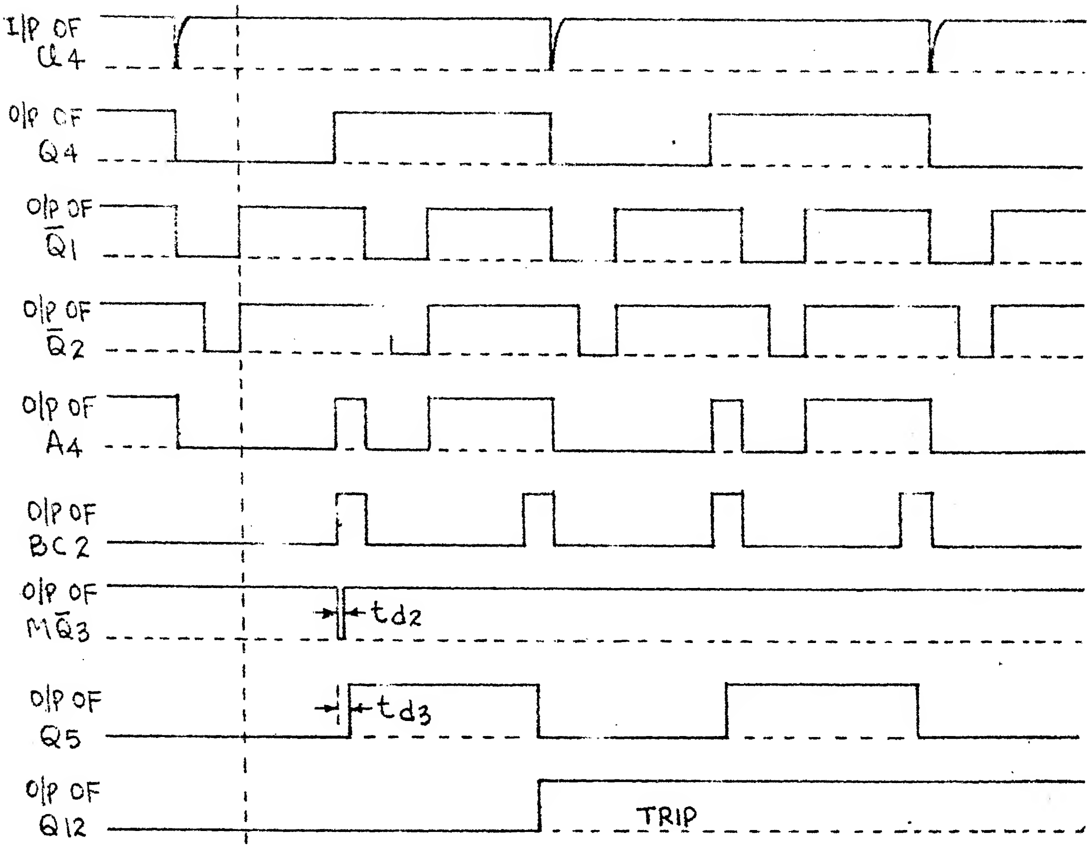


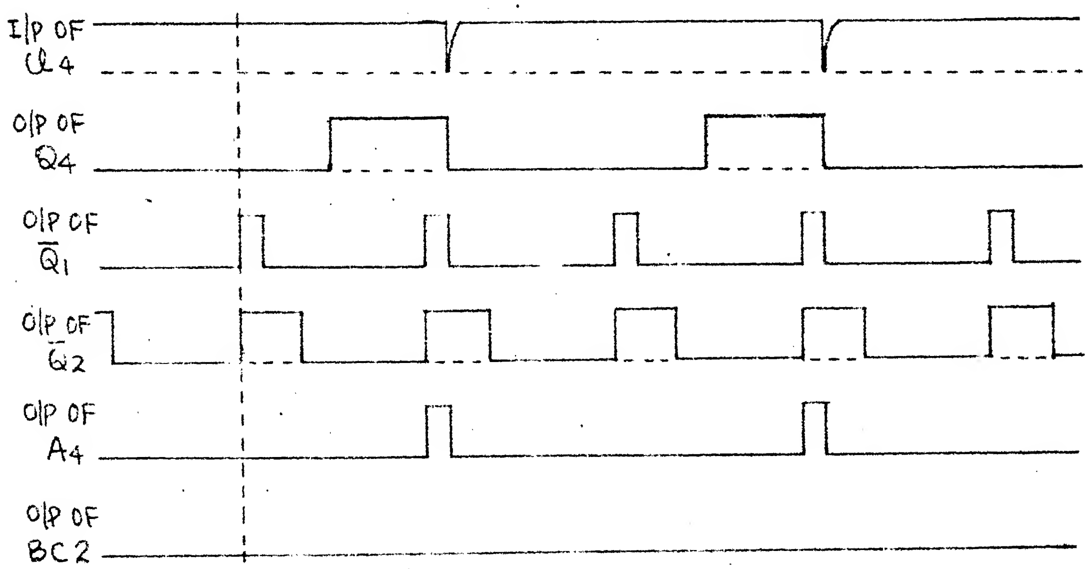
Fig. 4.4(a) FAULT IN ZONE-2

CONTINUED

FAULT IN ZONE-1 & ZONE-2



FAULT IN ZONE-3



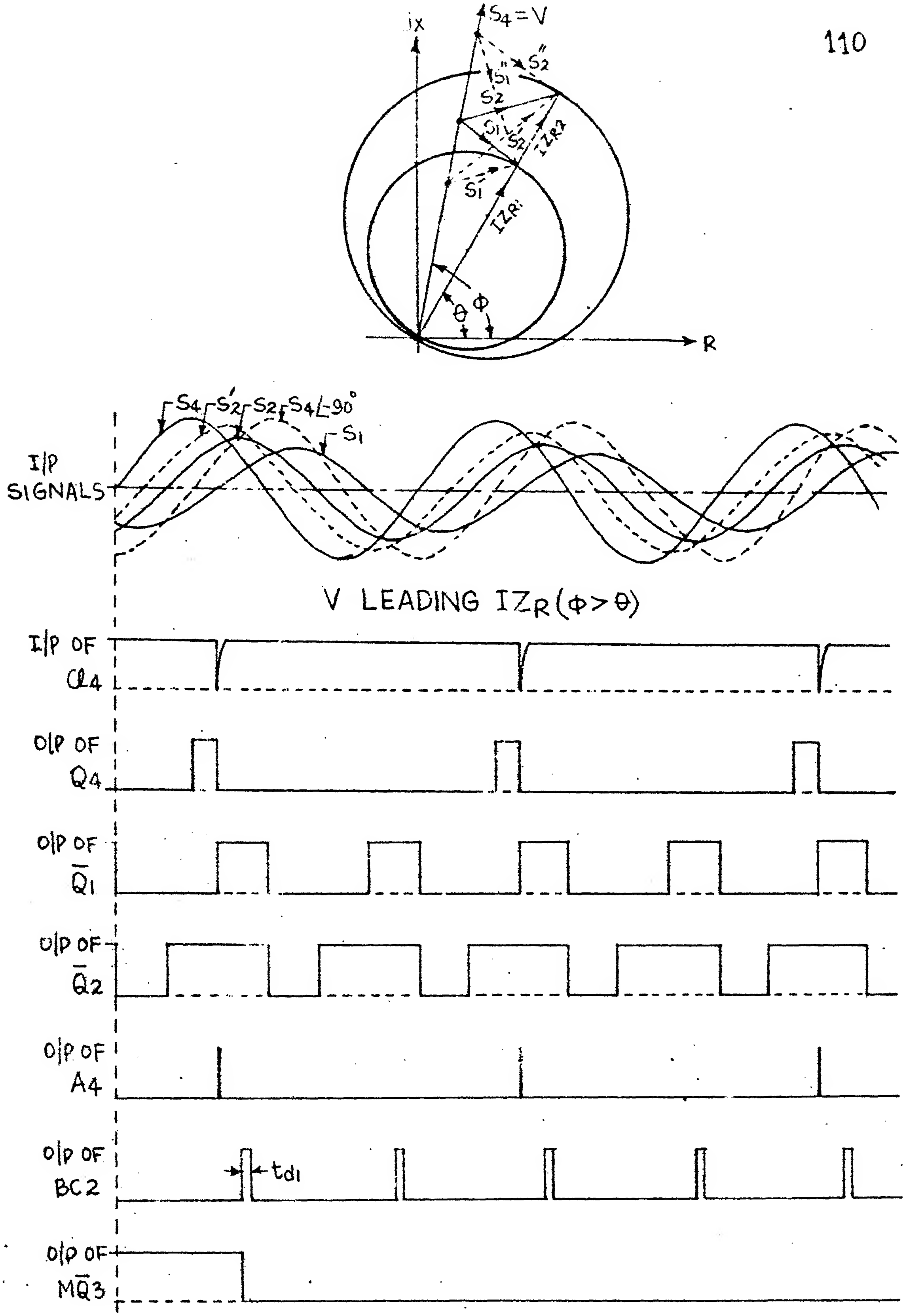
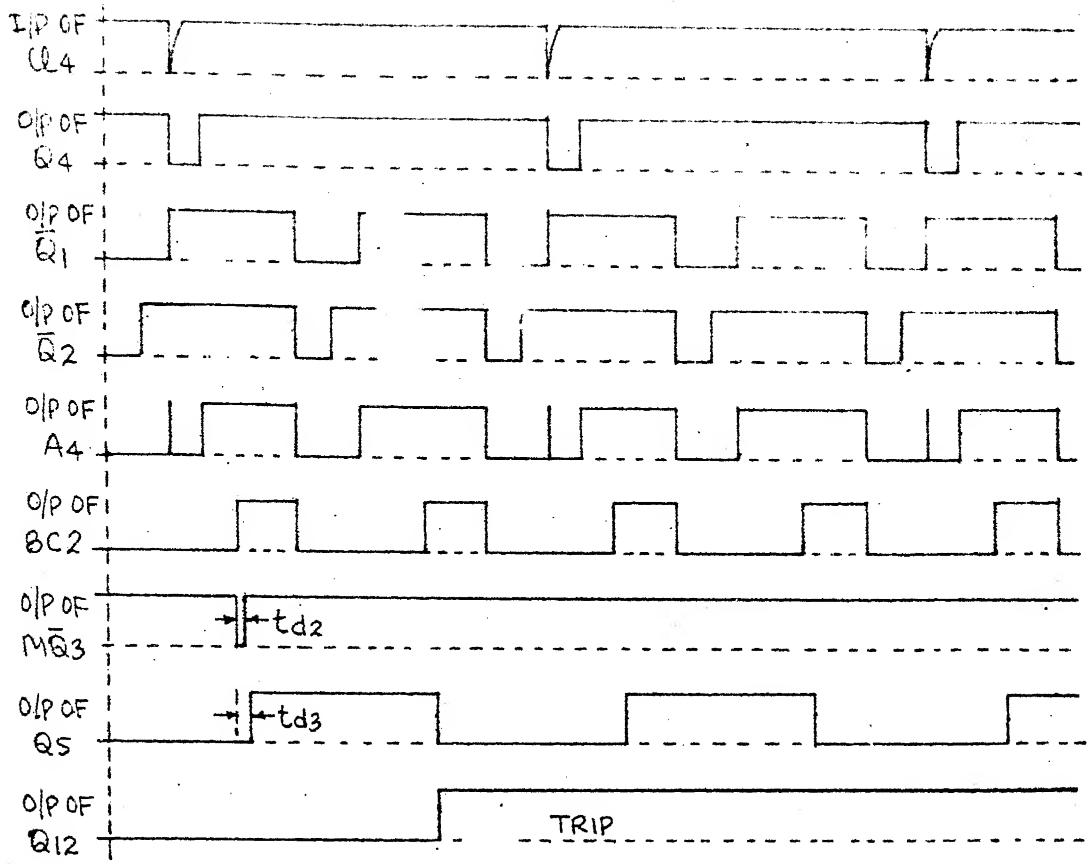


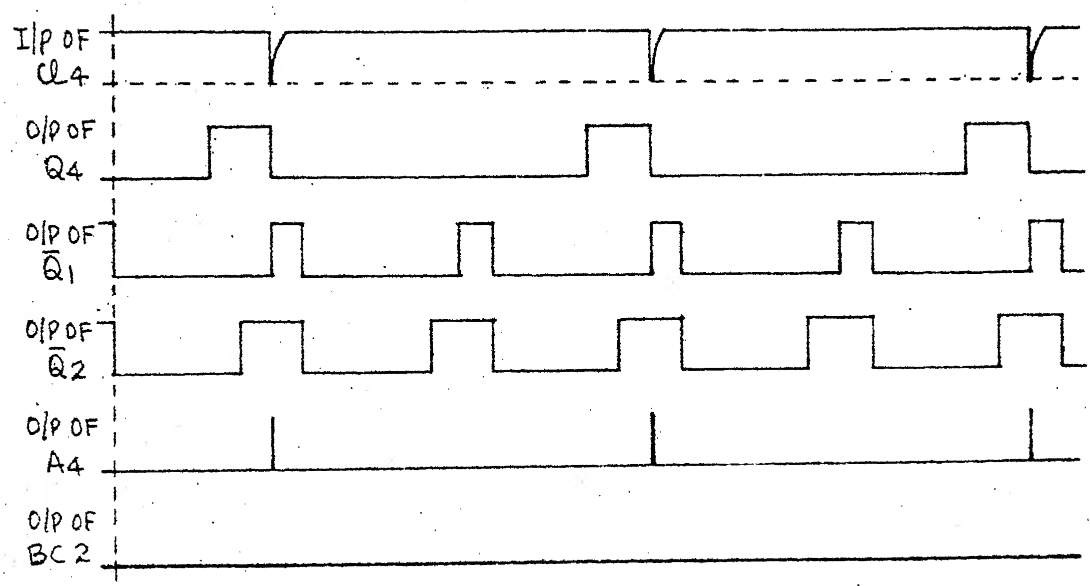
Fig. 4.4(b) FAULT IN ZONE-2

CONTINUED

FAULT IN ZONE-1 & ZONE-2



FAULT IN ZONE-3



pulse every half cycles which is resetted when the 'clear' of it goes to logic (1). The rest of the operation is similar to the upper comparator. The trip output of lower comparator through B-10 is OR gated with upper comparator to issue a final trip output via OR gate (O1 and O2). The shape of the characteristic of zone-3 can be changed by using variable angular critarian, by the change of clock frequency (f_1) where,

$$f_1 = \frac{f_o}{2-\beta_1/90} \qquad (4.4)$$

f_o = Frequency required to give $\pm$ 90° angular critarian

f_1 = " " variable " "

β_1 = Angular critarian (< 90°)

If the operating critarian is $\pm$ 60°, then, the required clock frequency

$$f_1 = \frac{3f_o}{4} \text{ , i.e. } f_1 > f_o \qquad (4.5)$$

The characteristic produced by lower comparator with new clock frequency is elliptical and hence tripping due to power - swing is avoided. Fig. 4.4(a) and 4.4(b) explains the operation of 3-zone phase-module.

The basic 2-input comparator, as described above, can be converted to multi-input comparator by connecting their inputs via 4-input AND and NOR gates. Hence, any desired pick-up characteristics can be produced by proper choice of input signals. The detailed circuit diagram of each phase module, with

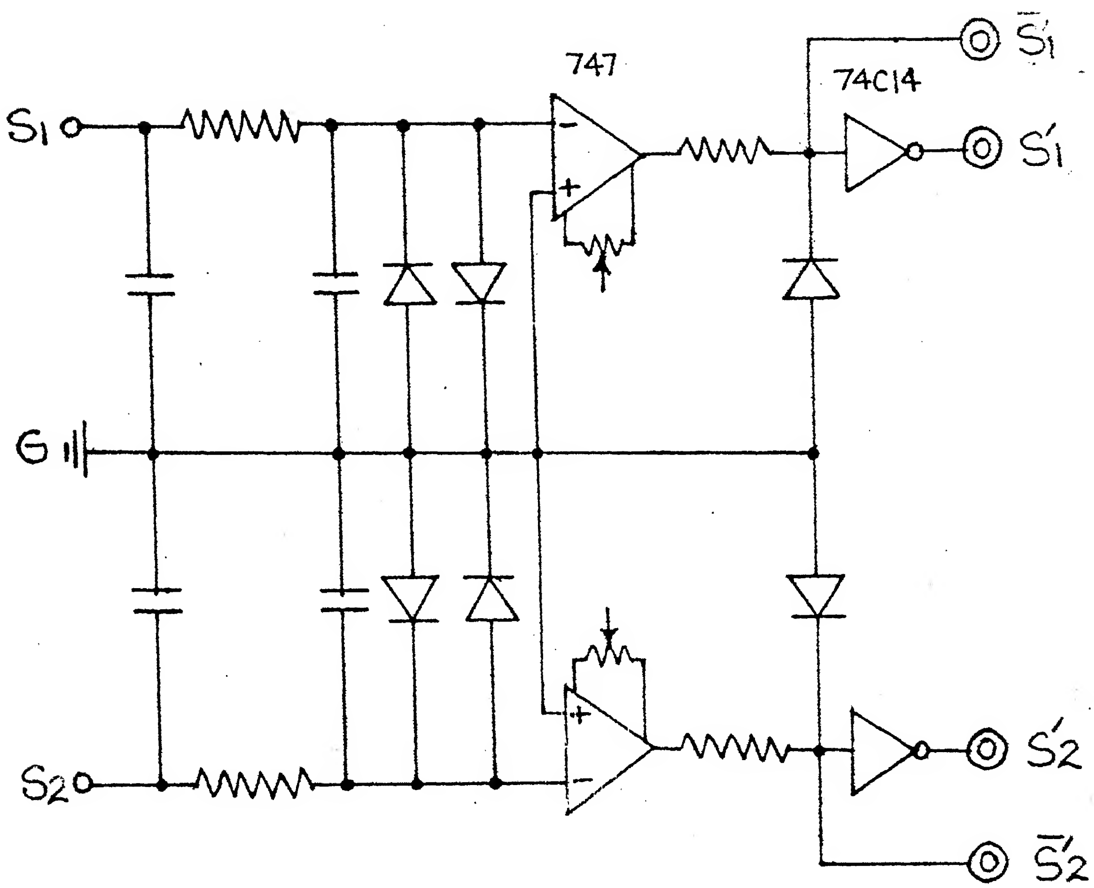


Fig. 4.5(a) SIGNAL PROCESSING UNIT

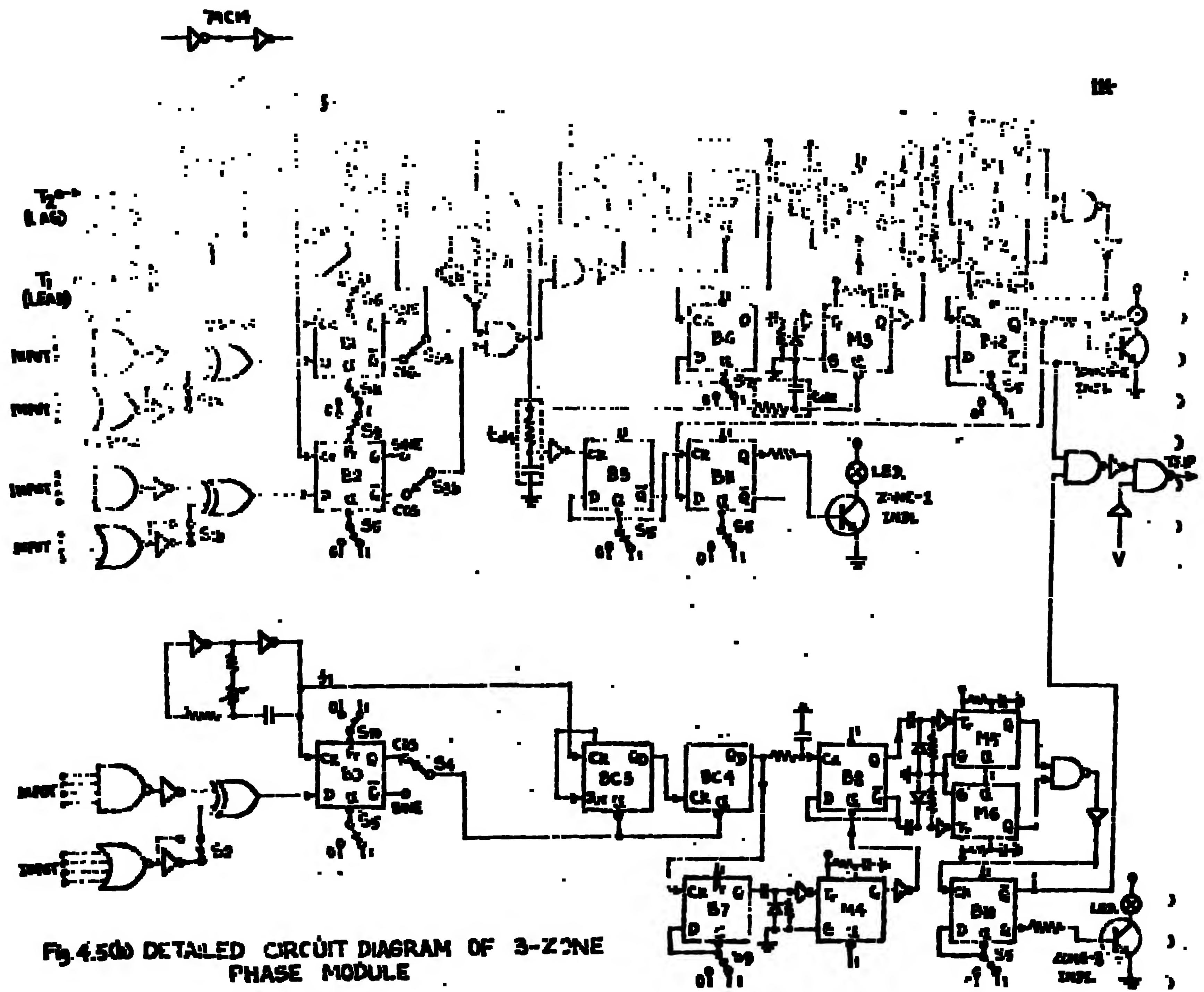


Fig.4.5(b) DETAILED CIRCUIT DIAGRAM OF 3-ZONE PHASE MODULE

multi-input operation and flexibility of using any zone at any time to provide any desired characteristic, is given by Fig. 4.5(b). It can be seen that Fig. 4.3 and Fig. 4.5(b) have different logic gates and IC's but they have same logic functions. This change of components was inevitable as CMOS Monostable IC's, AND gates and OR gates were not available to make the identical phase modules. Many function switches are used to make the relay versatile and flexible with all the benefits in one unit only. Fig. 4.5(a) gives the circuit diagram of signal processing unit for feeding to each phase - module.

4.2.3 Fabrication of a Versatile Phase Module:

The 3-zone phase module can be used in a variety of ways such as operation in zone-2 only, zone-2 as zone-1, zone 1 and 2, zone-3 only etc. A detailed study of circuit diagram (Fig. 4.5(b)) shows that logic state of clear (Cl) terminals of B-4, B-5 and B-8 are not in our control hence, they are not considered. Similarly the logic state of Preset (Pr) terminals of B-1, B-2 and B-9 are of importance, hence, they are considered. Input signals to each zone are important from the point of view of zone operation. Terminals T_1 and T_2 should also have proper logic state/signals for lead/lag compensation. Hence, a table can be made for different zone of operation by assigning suitable logic states to terminal

Table 4.1: Different Zone Operation for 2-Input Comparator

Sr. No.	INPUT OF Ex/OR TO	INPUT TO T_1/T_2	SIGNAL TO ZONE			CLEAR OF FLIP/FLOP									PRESET OF F/F			OUTPUT OF F/F			OPERATION IN ZONE
			I	II	III	1	2	3	6	7	9	10	11	12	1	2	9	1	2	9	
0	OR	X	X	X	X	1	1	X	X	X	X	X	X	X	0	0	0	$\bar{Q}$	$\bar{Q}$	Q	None
1	"	X	X	X	1	1	1	X	X	1	1	1	X	X	0	0	1	"	"	"	3
2	"	X	X	X	1	1	1	X	X	0	1	1	X	X	0	0	1	"	"	"	3→1
3	"	X	X	1	1	1	1	X	1	1	1	1	X	1	0	1	1	"	"	"	2,3
4	"	X	X	1	1	1	1	X	0	1	1	1	X	1	0	1	1	"	"	"	2→1,3
5	"	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	"	"	"	1,2,3
6	"	1	1	1	X	1	1	1	1	X	X	X	1	1	1	1	0	"	"	"	1,2
7	"	X	X	1	X	1	1	X	1	X	X	X	X	1	0	1	0	"	"	"	2
8	"	X	X	1	X	1	1	X	0	X	X	X	X	1	0	1	0	"	"	"	2→1

X = Don't care

0 = Logic zero

1 = Logic one or presence of signal

Exp (11.?)

Cl and Pr and proper signals to zones and terminals T_1 and T_2. Thus, a table is made with 9 different modes of operation of the phase module which could be useful for checking the proper operation of each zone with set time delay.

It can be seen from the Table 4.1 that, 'Cl' of flip/flops 1, 2,3,9,10,11 and 12 can be connected together through one switch whereas, 'Cl' of flip/flop 6 and 7 are independently controlled. Similarly, the 'Pr' of flip/flops 1,2 and 9 are independently controlled and their logic state depends upon operation of different zones. Thus, each phase module can be used in 9 different ways. The selection of operation of zone depends upon the available measuring signals. Fig. 4.6 gives the front panel lay out of the polyphase 3-zone distance relay with built-in power supply and signal processing unit.

4.3 MEASURING CIRCUIT OF POLYPHASE RELAY:

The schematic diagram given in Fig. 4.7 is a measuring circuit which provides the necessary signals to each phase module. Compensated fault point voltages V_x, V_y and V_z are provided to each phase module A,B and C along with line to ground voltages V_a, V_b and V_c. Zero-sequence current compensation is provided to each compensated voltages so that same measuring circuit gives the correct measurement of impedance for all types of line faults. The compensated fault point voltages can be derived as follows.

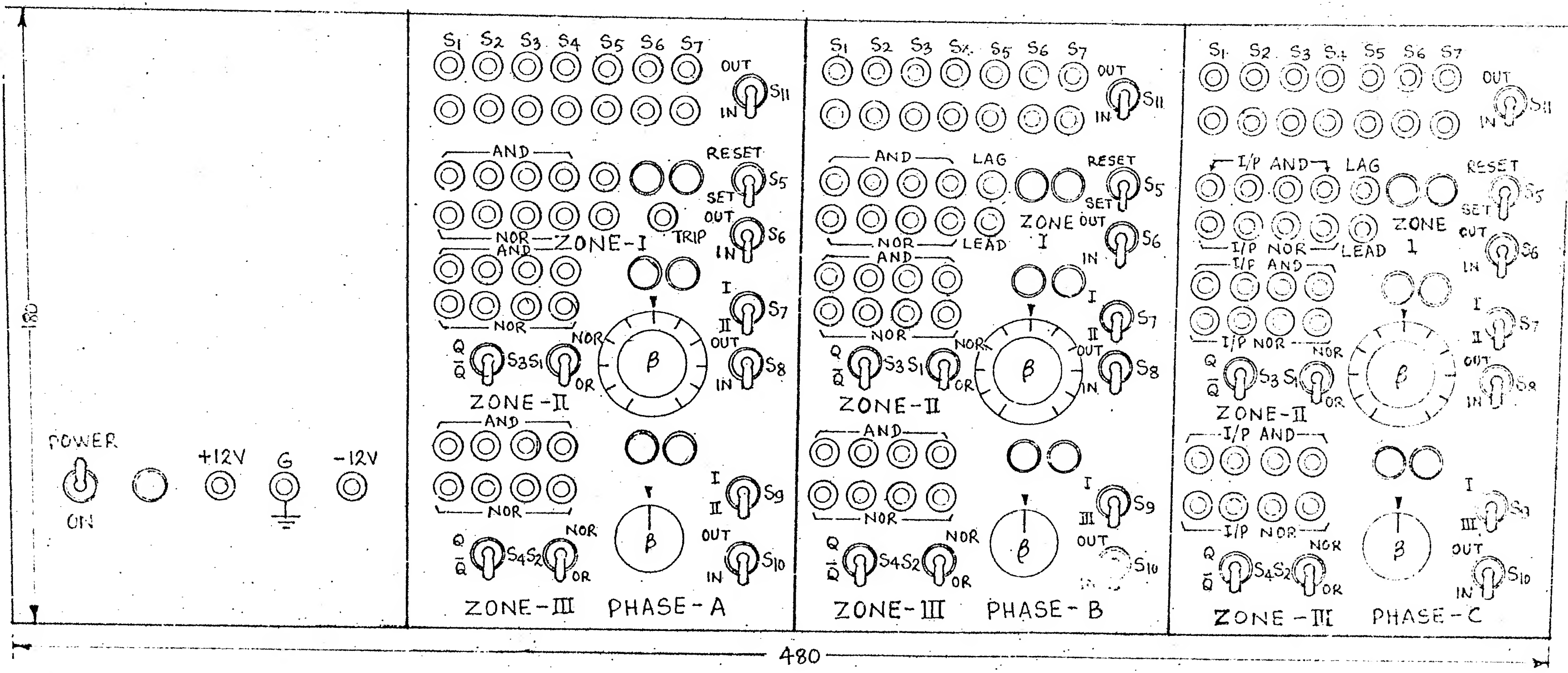


Fig.4.6 FRONT PANEL LAYOUT OF 3-ZONE POLYPHASE DISTANCE RELAY

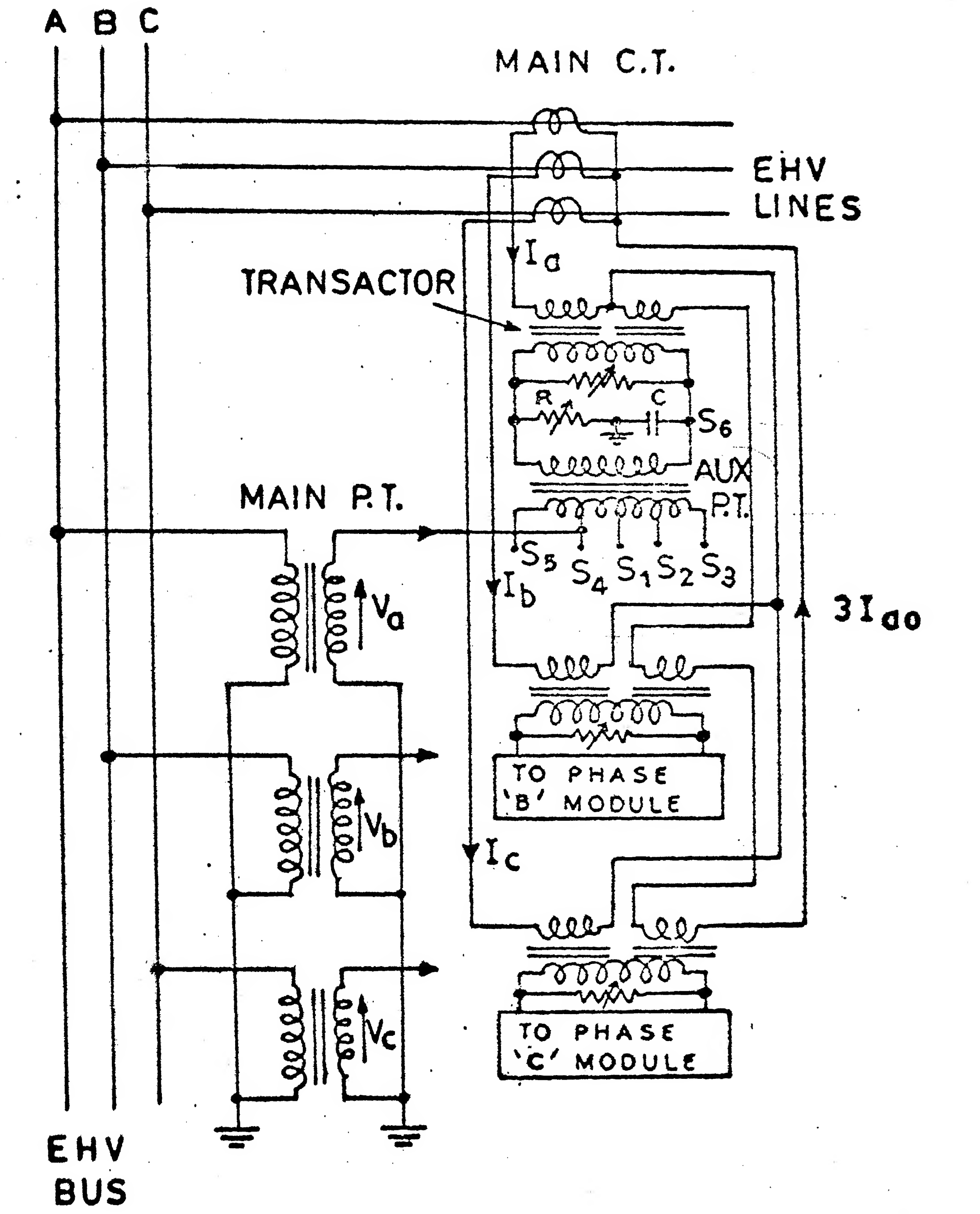


Fig.4.7 MEASURING CIRCUIT OF POLYPHASE RELAY

The line to neutral fault point voltage of phase 'a' during any type of short circuit, assuming no fault resistance is,

$$V_{fa} = V_a - I_a Z_L \tag{4.6}$$

Now converting I_a into its sequence components and also changing Z_L likewise, we get,

$$\begin{aligned} V_{fa} &= V_a - I_{a1}Z_{L1} - I_{a2}Z_{L2} - I_{a0}Z_{L0} \\ &= V_a - (I_a + kI_{ao})Z_{L1} \end{aligned} \tag{4.7}$$

where: $k = n-1$ and $n = Z_{L0}/Z_{L1}$

As $I_a = I_{a1}+I_{a2}+I_{a0}$ and $Z_{L1}=Z_{L2}$, the three compensated voltages are:

$$V_x = V_a-(I_a+kI_{a0})Z_R = V_{x1}+V_{x2}+V_{x0} \tag{4.8}$$

$$V_y = V_b-(I_b+kI_{a0})Z_R = \alpha^2 V_{x1}+\alpha V_{x2}+V_{x0} \tag{4.9}$$

$$V_z = V_c-(I_c+kI_{a0})Z_R = \alpha V_{x1}+\alpha^2 V_{x2}+V_{x0} \tag{4.10}$$

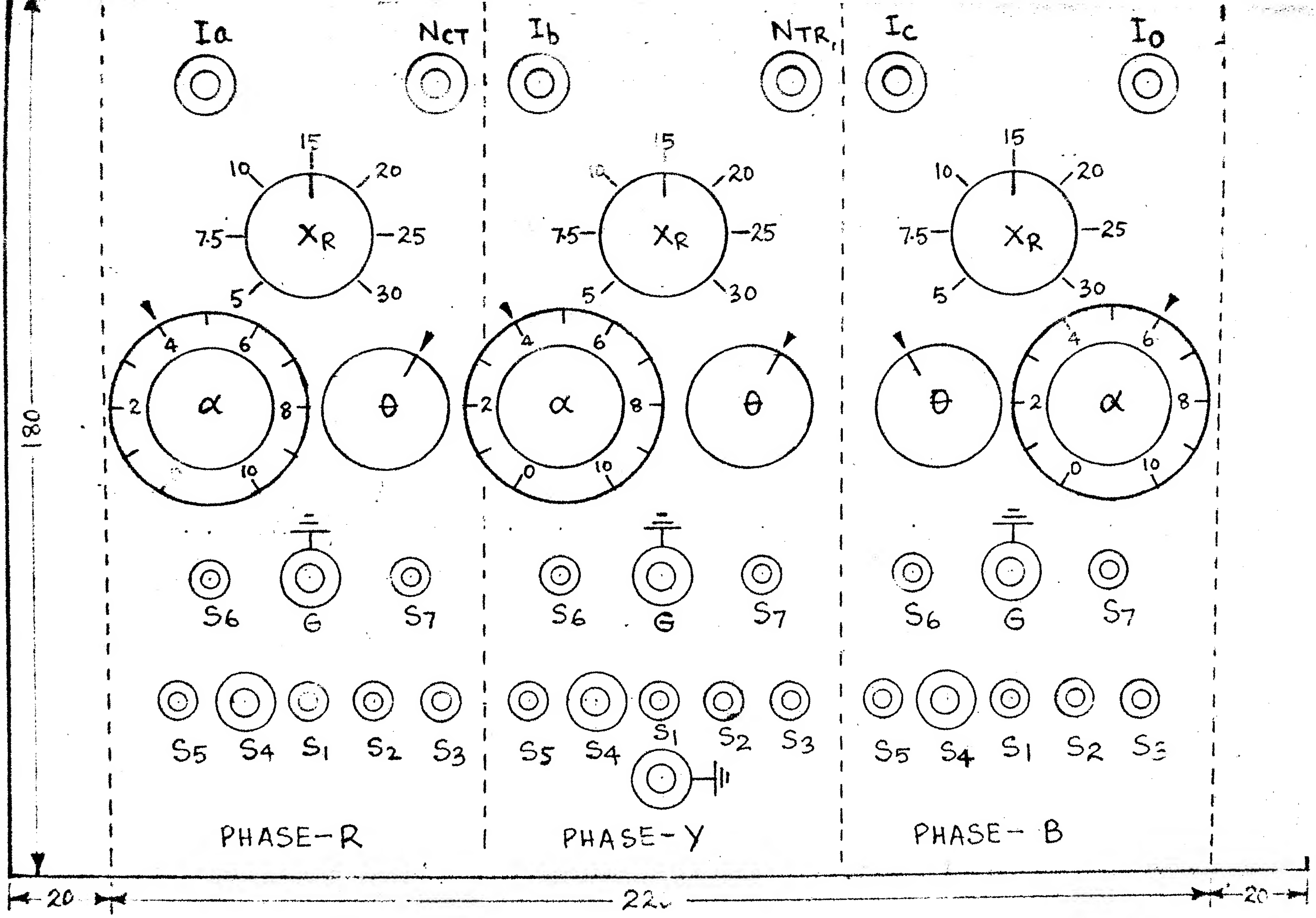
where, $Z_{L1} = Z_R$ = Replica impedance

and,

$$V_{x1} = V_{a1}-I_{a1}Z_R, V_{x2}=V_{a2}-I_{a2}Z_R \text{ and } V_{x0}=V_{a0}-I_{a0}Z_R\, n \tag{4.11}$$

4.3.1 Signals for Classical Characteristics:

The signal provided to phase-A module are V_a and $-V_x$, to phase-B module are V_b and $-V_y$ and to phase-C module are V_c and $-V_z$. The auxillary P.T. is used to provide 3-zone


Ia
NCT
Ib
NTR
Ic
Io
XR
α
θ
S6
G
S7
S5
S4
S1
S2
S3
PHASE-R
PHASE-Y
PHASE- B
180
20
22
20

operation of each phase with a certain percentage of 1st zone impedance Z_{R1}. A phase-splitter (R and C) across IZ_{R1} provide directional signals IR and IX. As the signals to each comparator are V and IZ_R-V, each phase module characteristics will be mho type. The final characteristic of the relay will be a combination of these characteristics, depending upon the type of faults and it can be predicted mathematically. The pick-up characteristics of scheme-I is shown by Fig. 4.9.

4.3.2 Fabrication of Measuring Unit:

The front panel layout of the measuring unit is shown by Fig. 4.8. The Measuring Unit consists of three identical sets of Transactors and Auxillary Potential Transformer (Aux. P.T.). The main primary of each transactor is designed to carry a phase current of 5A and an additional winding provides the compensation due to zero sequence current. The secondary is a potential winding having multi-tappings so that a different voltages, proportional to current, is produced at each position of the selector switch. Thus, the replica reactance can vary from 5 ohm to 30 ohm. A wire-wound pot is connected across this secondary so as to vary the phase angle (θ) of the replica impedance. The variation of w.w. pot also changes the magnitude of the induced voltage or replica impedance, hence, it is necessary to measure the magnitude for different values of replica impedance angle. A w.w. pot and

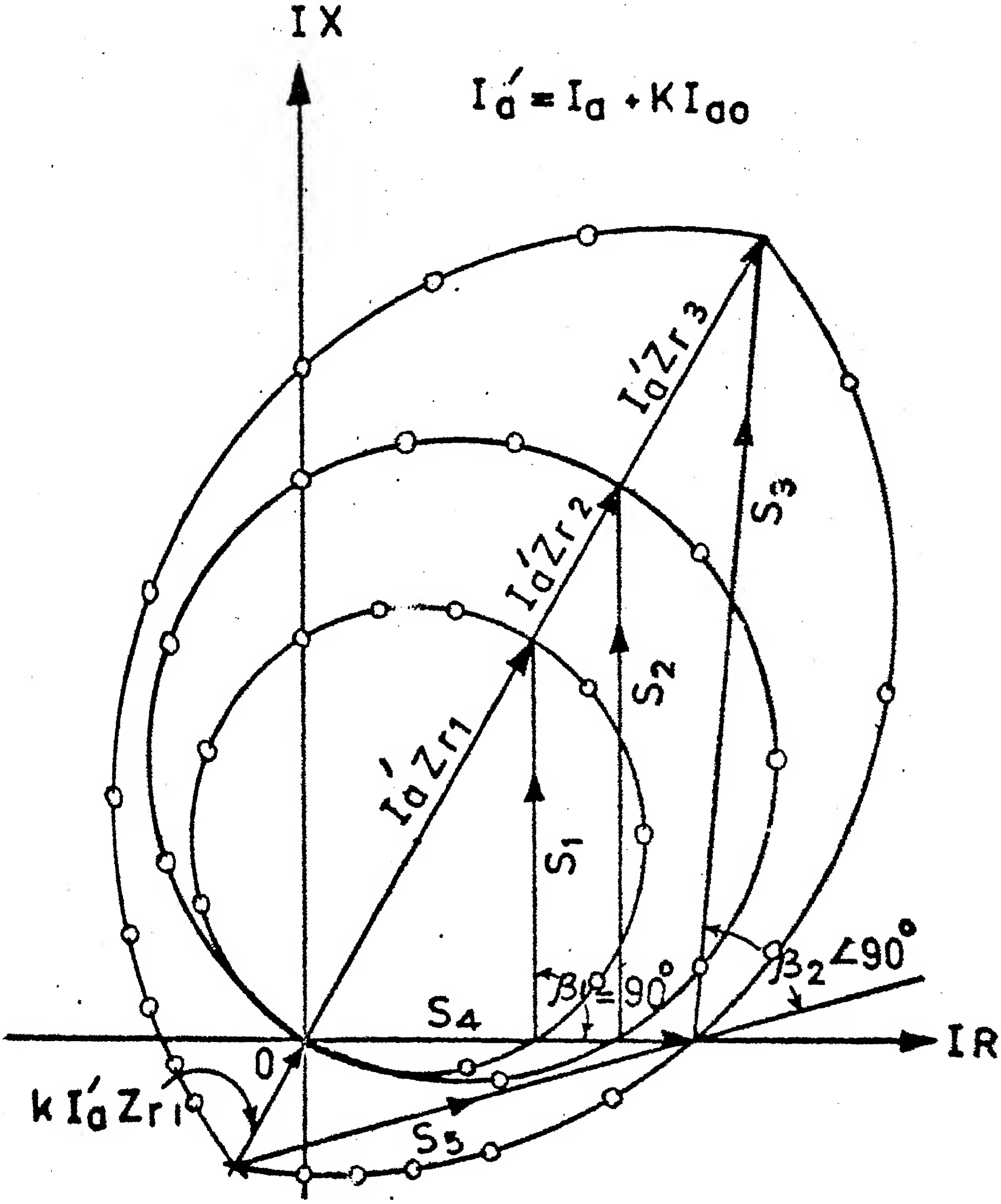


FIG. 4.9 FINAL CHARACTERISTIC OF PHASE 'A' MODULE (SCHEME -1)

a capacitor is connected across the primary of Aux. P.T. so as to provide a signal (S_6, S_7) whose angle can be changed w.r.t. IR axis. The secondary of Aux. P.T. provides the required signals (S_1 to S_5) to each phase module in a rather novel way. The zone-2 impedance is set at 150% and zone-3 impedance is set at 200% of zone-1 impedance. The voltage signal (S_4) is provided by main P.T's and phase currents by 3 sets of identical C.T's which are externally connected to Measuring Unit. The measuring unit is housedin a standard bin of size 180x220.

4.4 POLYPHASE RELAY BY USE OF MULTI-INPUT COMPARATORS:

The 2-input comparator as described earlier, can be converted to multi-input comparator by slight change, using AND/NOR gates as shown by Fig. 4.10(a). It can be seen that each elementsof the comparator can handle 4-inputs and hence, any desired pick-up characteristic can be obtained. The signals provided to each comparators are from the same measuring circuit as described earlier.

4.4.1 Proposed Scheme-II (Modified Mho Characteristics):

The classical characteristic used for protection of EHV transmission lines has one serious drawback that, the area enclosed by the pick-up characteristic is very large. Thus, there are chances that, the relay on the heavily loaded transmission lines may give false tripping due to

Table 4.2: Signals and Logic for Different zone Operation for Multi-input Comparator.

Sr. No.	INPUT OF Ex/OR TO	INPUT TO T_1/T_2	SIGNAL TO ZONE			CLEAR OF FLIP/FLOP									PRESET OF FLIP/FLOP			OUTPUT OF FLIP/FLOP			OPERATION IN ZONE
			I	II	III	1	2	3	6	7	9	10	11	12	1	2	9	1	2	9	
0	NOR	X	X	X	X	1	1	X	X	X	X	X	X	X	0	0	0	$\bar{Q}$	$\bar{Q}$	Q	None
1	"	X	X	X	1	1	1	X	X	1	1	1	X	X	0	0	1	$\bar{Q}$	$\bar{Q}$	$\bar{Q}$	3
2	"	X	X	X	1	1	1	X	X	0	1	1	X	X	0	0	1	$\bar{Q}$	$\bar{Q}$	$\bar{Q}$	3→1
3	"	X	X	1	1	0	1	X	1	1	1	1	X	1	1	1	1	Q	Q	$\bar{Q}$	2,3
4	"	X	X	1	1	0	1	X	0	1	1	1	X	1	1	1	1	Q	Q	$\bar{Q}$	2→1,3
5	"	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	Q	Q	$\bar{Q}$	1,2,3
6	"	1	1	1	X	1	1	1	1	X	X	X	1	1	1	1	0	Q	Q	Q	1,2
7	"	X	X	1	X	0	1	X	1	X	X	X	X	1	1	1	0	Q	Q	Q	2
8	"	X	X	1	X	0	1	X	0	X	X	X	X	1	1	1	0	Q	Q	Q	2→1

X = Don't care

0 = Logic zero

1 = Logic one or presence of signal

Ex/r

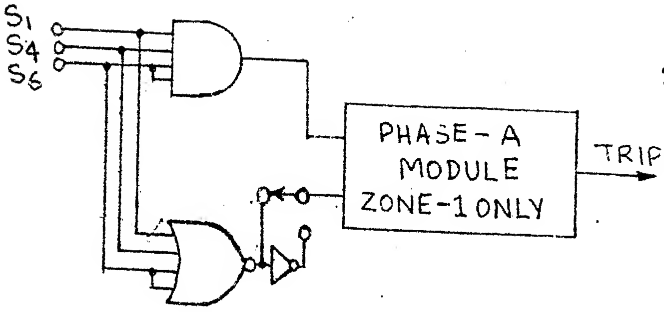


Fig. 4.10(a) CONVERSION OF 2-INPUT TO MULTI-INPUT COMPARATOR

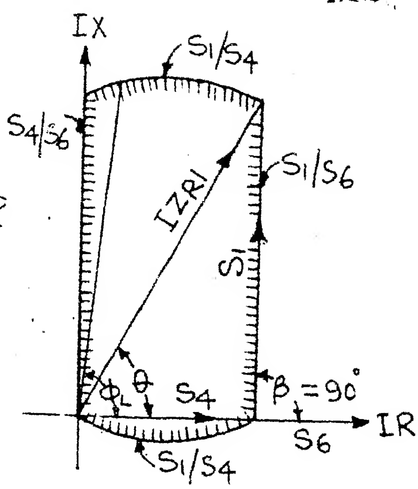
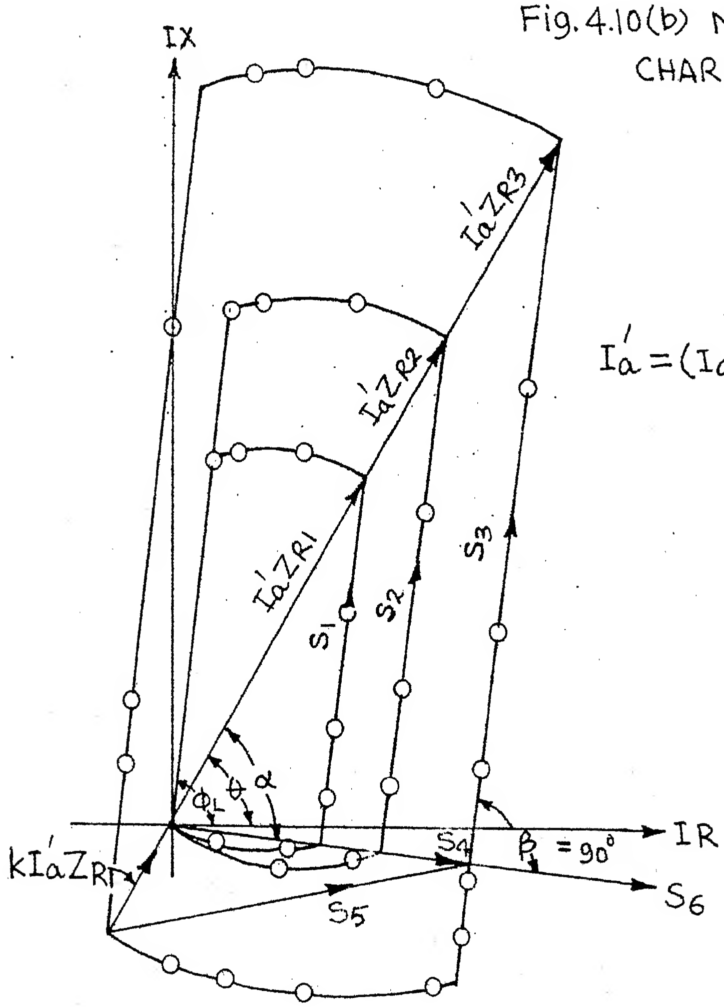


Fig. 4.10(b) MODIFIED MHO CHARACTERISTIC



$I'_a = (I_a + kI_{a0})$

Fig. 4.10(c) FINAL CHARACTERISTIC OF PHASE 'A' MODULE (SCHEME – II)

sudden overloads and power swing. Hence, if blinders can be used as shown by Fig. 4.10(b) the modified mho characteristic could be obtained which is ideal for the protection of heavily loaded EHV lines. It can be seen that, the modified (mho) characteristic is more or less quadrilateral which is compatible with any type of line fault with arcing resistance. This type of characteristic could be obtained by the use of 3-signals only as shown below and using multi-input comparator.

$$\text{Let } S_1 = IZ_{R1}-V$$
$$S_4 = V$$
$$\text{and } S_6 = IR \tag{4.12}$$

A 2-input comparator of each phase module can be converted to multi-input comparator by the use of AND and NOR gates as shown by Fig. 4.10(a). These composite characteristics can be realised by the technique given by Humpage and Sabberwal [31].

Modified mho characteristic can be realised for poly-phase 3-zone relay by the use of multi-input comparator and only 3-signals are needed for each zone of each phase module as shown:

$$S_1 = (I_a+kI_{ao})\, Z_{R1}-V_a$$
$$S_4 = V_a$$
$$S_6 = k_1(I_a+kI_{ao})Z_{R1}\underline{/-90+\phi-\theta} \quad \text{For zone-1 characteristic}$$
$$= IR\ \underline{/-90+\phi} \tag{4.13}$$

$$S_2 = (I_a + kI_{ao})Z_{R2} - V_a$$

$$S_4 = V_a$$

$$S_6 = k_1(I_a + kI_{ao})Z_{R1}\underline{\angle -90+\phi-\theta} \quad \text{For zone-2 characteristics}$$

$$= IR \angle -90+\phi \qquad (4.14)$$

$$S_3 = (I_a + kI_{ao})Z_{R3} - V_a$$

$$S_5 = k(I_a + kI_{ao})Z_{R3} + V_a$$

$$S_6 = k_1(I_a + I_{ao})Z_{R1} \underline{\angle -90+\phi-\theta} \quad \text{For zone-3 characteristics}$$

$$= IR \underline{\angle -90+\phi} \qquad (4.15)$$

The resultant characteristic of phase-A module is shown by Fig. 4.10(c), where the operating criterian is

$$-90^\circ \le \beta \le 90^\circ$$

4.4.2 Proposed Scheme-III (Quadrilateral Characteristic):

A relay with quadrilateral characteristic is ideal for the protection of heavily loaded EHV transmission lines as the area covered by it is minimum and it is compatible with any type of line fault having arcing resistance. 4-signals are required for each zone to produce a quadrilateral characteristic for 3-zone operation. The signals required for each phase module are:

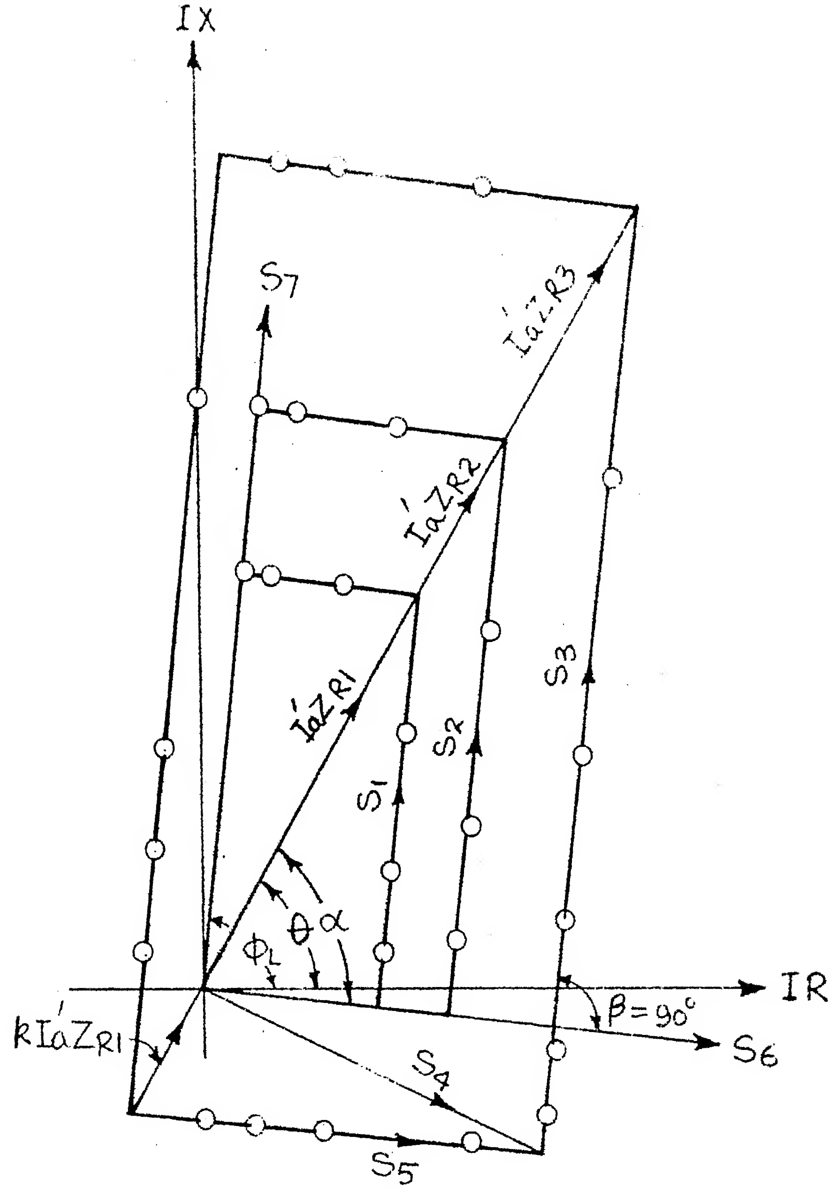


Fig.4.10(d) FINAL CHARACTERISTIC OF PHASE-'A' MODULE (SCHEME-III)

$$S_1 = (I_a + kI_{ao})Z_{R1} - V_a$$

$$S_4 = V_a$$

$$S_6 = k_1(I_a + kI_{ao})Z_{R1}\underline{/-90+\phi-\theta} \quad \text{For zone-1 characteristic}$$

$$S_7 = S_6\underline{/90} \longrightarrow \text{where is it?} \qquad (4.16)$$

$$S_2 = (I_a + kI_{ao})Z_{R2} - V_a$$

$$S_4 = V_a$$

$$S_6 = k_1(I_a + kI_{ao})Z_{R1}\underline{/-90+\phi-\theta} \quad \text{For zone-2 characteristic}$$

$$S_7 = S_6\,\underline{/90} \qquad (4.17)$$

$$S_3 = (I_a + kI_{ao})Z_{R3} - V_a$$

$$S_5 = k(I_a + kI_{ao})Z_{R3} + V_a$$

$$S_6 = k_1(I_a + kI_{ao})Z_{R1}\underline{/-90+\phi-\theta} \quad \text{For zone-3 characteristic}$$

$$S_7 = S_6\underline{/90} \qquad (4.18)$$

The resultant characteristic of phase-A module is given by Fig. 4.10(d), where the operating critarian is

$$-90^{\circ} \leq \beta \leq 90^{\circ}$$

It can be seen from the above equations that, 4th signal is a function of 3rd signal hence, in fact, only 3 different signals are required from the measuring circuit.

4.5 TESTING:

The signal provided to each phase modules are rather unusual and thus, a novel way is used to generate these signals

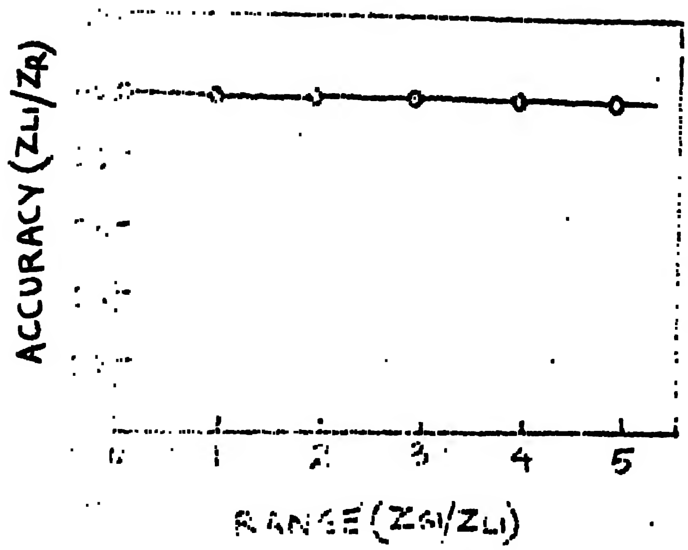


Fig. 4.11(a) ACCURACY VS. RANGE CURVE

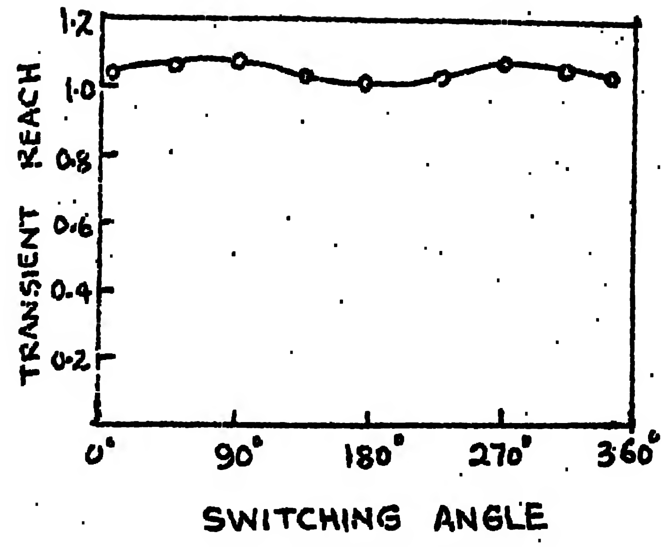


Fig. 4.11(b) TRANSIENT REACH VS. SWITCH. ANGLE OF FAULT CURRENT

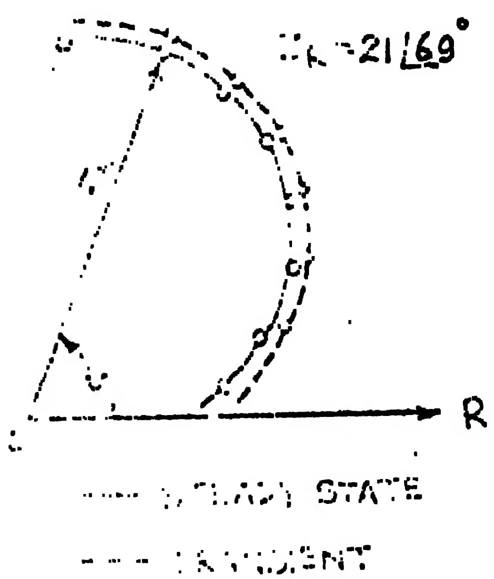


Fig. 4.11(c) POLAR CURVES

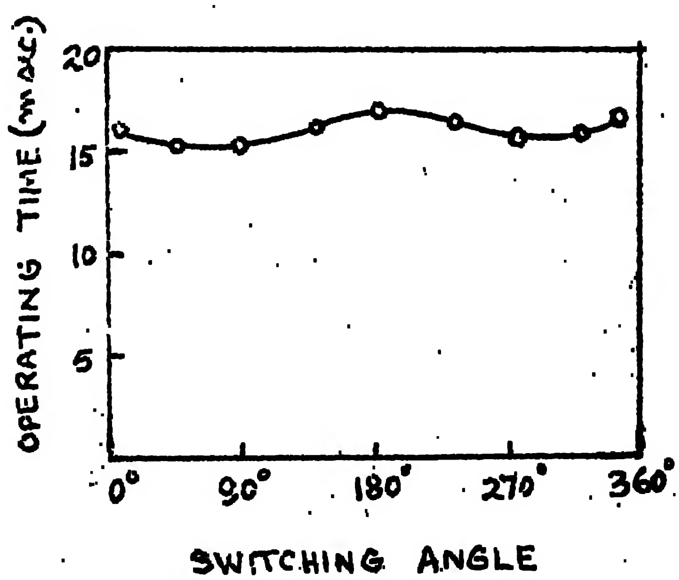


Fig. 4.11(d) OPERATING TIME VS. SWITCH. ANGLE OF FAULT CURRENT

through Measuring Unit. A single-phase dynamic test bench has been designed and fabricated to test the hard-ware implementation of all the Digital Phase Distance Relay/Comparator. The Dynamic Test Bench has an overallaccuracy of higher than ±5%. [illegible] The following tests were performed on the polyphase relay for all single line to ground faults. why only for S.L.G. faults

a) Open circuit line energised and de-energised from the bus-bar, the relay was found to be completely stable.

b) The accuracy (Z_{L1}/Z_R) under steady-state condition and transient condition w.r.t. 'Range' (Z_{S1}/Z_{L1}) was plotted against the 'Range' as shown by Fig. 4.11(a). It can be seen that, at a range of 5 the under-reach is < 5%.

c) The dynamic characteristic of the relay was plotted for different phase angles of line impedance. A transient over-reach of less than 5% near the balance point is observed.

d) The accuracy under transient state w.r.t. switching angle of fault current was plotted as shown by Fig.4.11(b) The transient over-reach of 10% is observed. is not acceptable

e) The relay operating time was plotted against the switching angle of fault current and is found to vary between 15 to 18 msec.

f) Relay was tested for reverse fault by passing steady-state and transient current through the transactor in reverse direction to the normal flow of current, the relay was found to be completely stable.

4.6 MATHEMATICAL ANALYSIS FOR CLASSICAL CHARACTERISTIC:

The signals to phase module (A) for 1st and 2nd zone operation are

$$S_1 = -V_x = (I_a+kI_{ao})Z_{R1}-V_a$$

$$S_2 = (I_a+kI_{ao})Z_{R2}-V_a$$

and $S_4 = V_a$ (4.19)

Hence,

$$\frac{S_1}{S_4} = \frac{-V_x}{V_a} = \frac{(I_a+kI_{ao})Z_{R1}-V_a}{V_a} \quad (4.20)$$

$$= \frac{Z_{r1}}{V_a/(I_a+kI_{ao})} - 1$$

$$= \frac{Z_{r1}-Z}{Z} \quad \text{where } Z = \frac{V_a}{(I_a+kI_{ao})}$$

If,

$$\frac{-V_x}{V_a} = \beta = \frac{Z_{r1}-Z}{Z} \quad (4.21)$$

and critarion for tripping is $-90^\circ \leq \beta \leq 90^\circ$,

then the characteristic will be mho,passing through origin, will satisfy above condition. The characteristic for L-G faults of different phases will be similar.

The signals to phase module (A) for 3rd zone operation are:

$$S_3 = (I_a+kI_{ao})Z_{r3}-V_a$$

and

$$S_5 = k(I_a+kI_{ao})Z_{r3}+V_a \tag{4.22}$$

Hence,

$$\frac{S_3}{S_5} = \frac{(I_a+kI_{ao})Z_{r3}-V_a}{k(I_a+kI_{ao})Z_{r3}+V_a} \tag{4.23}$$

$$= \frac{Z_{r3}-Z_L}{kZ_{r3}+Z_L} \quad \text{where } Z_L = \frac{V_a}{(I_a+kI_{ao})}$$

$$\text{If } \angle\frac{S_3}{S_5} = \beta_1 = \frac{Z_{r3}-Z_L}{kZ_{r3}+Z_L} \tag{4.24}$$

and critarion for tripping is $-60^\circ \leq \beta_1 \leq 60^\circ$, then the characteristic will be offset-elliptical enclosing the origin and hence, it will be also immune to power-swing. The final characteristic of each phase module is shown by Fig. 4.9(~~c~~).

4.7 CONCLUSION:

The proposed polyphase 3-zone distance relay has 3-identical phase modules using digital and linear IC's and is compact with minimum of hardware. This relaying scheme has been designed, fabricated and tested on the Dynamic Test Bench which is also designed and fabricated by us. This relaying scheme

is flexible enough to produce any desired characteristics which are useful for special applications. The relaying scheme with modified mho characteristic (Scheme-II) and quadrilateral characteristic (scheme-III) has been tested with steady-state signals only. The observed characteristic matches well with the theoretical ones. The dynamic performance of relaying scheme-I has been checked and found to be within limits.

why

The polyphase distance relaying scheme presented in this chapter is free from most of the drawbacks of the conventional and existing relays and at the same time, the present relaying scheme is simple, compact, efficient, reliable and economical.

Table 4.1 For Fig. 4.9

Observation for Classical Characteristics (Scheme-I)

$\theta=60^{\circ}$, $I_a'Z_{R1}=6.2V$, $I_a'Z_{R2}=8.7V$, $I_a'Z_{R3}=12.5V$, $kI_a'Z_{R1}=2.0V$

S.No.	$\angle\frac{V}{IR}$ (Degrees)	CRITICAL VALUE OF 'V' FOR TRIP AT		
		$Z_{R1}, \beta_1 \leq \pm 90^{\circ}$ (volts)	$Z_{R2}, \beta_1 \leq \pm 90^{\circ}$ (volts)	$Z_{R3}, \beta_2 \leq \pm 70^{\circ}$ (volts)
1	-90	-	-	1.8
2	-70	-	-	1.8
3.	-50	-	-	2.2
4.	-30	-	-	2.8
5	-10	2.2	2.8	4.3
6	0	3.2	4.4	5.4
7	10	4.0	5.5	6.5
8	30	5.4	7.4	9.2
9	50	6.0	8.4	11.6
10	70	6.1	8.5	11.5
11	80	5.8	8.1	10.3
12	90	5.2	7.4	8.8
13	110	3.9	5.5	6.3
14	130	2.1	2.9	4.1
15	150	-	-	2.7
16	170	-	-	2.2
17	190	-	-	1.8
18	210	-	-	1.7

Table 4.2 For Fig. 4.10(c)

Observation for Modified Mho Characteristics (Scheme-II)

$\theta=60^{\circ}$, $\phi_L = 84^{\circ}$, $\beta \leq \pm 90^{\circ}$

$I_a^{\prime}Z_{R1}=6.2$, $I_a^{\prime}Z_{R2}=8.7V$, $I_a^{\prime}Z_{R3}=12.5V$, $kI_a^{\prime}Z_{R1}=2.0V$

Sr. No.	$\angle\frac{V}{IR}$ (Degrees)	Critical Values of 'V' for Trip at		
		Z_{R1}, (volts)	Z_{R2}, (volts)	Z_{R3}, (volts)
1	-90	-	-	2.1
2	-70	-	-	2.5
3	-50	-	-	3.3
4	-30	-	-	5.0
5	-20	1.4	2.1	5.0
6	-10	2.2	3.2	4.9
7	0	2.5	3.6	4.8
8	10	2.6	3.7	5.1
9	30	3.1	4.5	6.1
10	50	4.5	6.5	8.8
11	70	6.1	8.6	12.3
12	80	5.8	8.2	11.8
13	84	5.6	8.0	11.6
14	90	-	-	7.3
15	110	-	-	1.9
16	130	-	-	1.2

Table 4.3 For Fig. 4.10(d)

Observation for Quadrilateral Characteristics (Scheme-III)

$\theta = 60^\circ$, $\phi_L = 84^\circ$, $\beta \leq \pm 90^\circ$

$I_a'Z_{R1}=6.2V$, $I_a'Z_{R2}=8.7V$, $I_a'Z_{R3}=12.5V$, $kI_a'Z_{R1}=2.0V$

Sr. No.	$\angle \frac{V}{IR}$ (degrees)	Critical value of 'V' for Trip at		
		Z_{R1}, (volts)	Z_{R2}, (volts)	Z_{R3}, (volts)
1	-90	-	-	1.8
2	-70	-	-	2.0
3	-50	-	-	2.6
4	-30	-	-	4.4
5	-20	-	-	5.2
6	-10	-	-	5.1
7	10	2.6	3.7	5.3
8	30	3.1	4.4	6.3
9	50	4.5	6.3	9.0
10	70	5.8	8.2	11.8
11	80	5.7	8.0	11.4
12	84	5.7	8.0	11.4
13	90	-	-	8.1
14	100	-	-	3.3
15	110	-	-	2.0
16	150	-	-	1.0

TABLE 4.6 For Fig.4.11(a)

Observation for Range and Accuracy of MhO Relay

S.NO.	Z_R (Ohms)	Z_S (Ohms)	Z_L (Ohms)	Range $Y=Z_S/Z_L$	C.T.Ratio N_1	P.T.Ratio N_2	Steady State		Transient State	
							V for Trip (Volts)	Accuracy (x)	V for Trip (Volts)	Accurac x
1	10.77	9.5	10.8	0.88	2.3	2.3	52	1	52	1
2	10.77	15.5	10.8	1.44	2.3	2.3	41	1	40	0.976
3	10.77	19.5	10.8	1.80	2.3	2.3	36	1	36	1
4	10.77	23.5	10.8	2.18	2.3	2.3	32	1	31.5	0.981
5	5.5	23.5	5.0	4.70	2.5	2.3	18	0.978	17.5	0.972

TABLE 4.7 For Fig.4.11(c)

Observation for MhO Characteristic and Transient Over Reach

$Z_S = 23.5\angle 37^\circ$, $Z_R = 21\angle 69^\circ$

S. NO	$\angle Z_L/Z_R$ (Degrees)	Z_L (Ohms)	I_L (Amps.)	C.T. RATIO N_1	P.T. RATIO N_2	V for Trip at steady state (Volts)	V for Trip Transient state (Volts)	Z (Ohms)	Accuracy 'x' At steady state	Accuracy 'x' At transient state
1	+16	20.5	5.2	2.5	2.3	44	46	21.15	1.013	1.046
2	0	21.44	5.15	2.5	2.3	46	47	22.33	1.063	1.022
3	-10	22.53	4.90	2.2	2.3	48	50	21.55	1.042	1.042
4	-20	25.04	4.50	1.9	2.3	49	51.5	20.69	1.048	1.051
5	-30	23.5	4.80	1.9	2.3	49	52	19.40	1.066	1.061
6	-40	21.15	5.22	1.9	2.3	48	50.5	17.50	1.085	1.052
7	-50	18.94	5.83	1.9	2.3	43	46	14.02	1.038	1.070
8	-60	41.5	3.46	1.9	2.3	20	22.2	10.98	1.046	1.11

TABLE 4.8 For Fig.4.11(b) and 4.11(d)

"Observation for Transient Reach and Relay Operating Time"

$Z_S = 23 \angle 87°$, $Z_R = 21 \angle 69°$

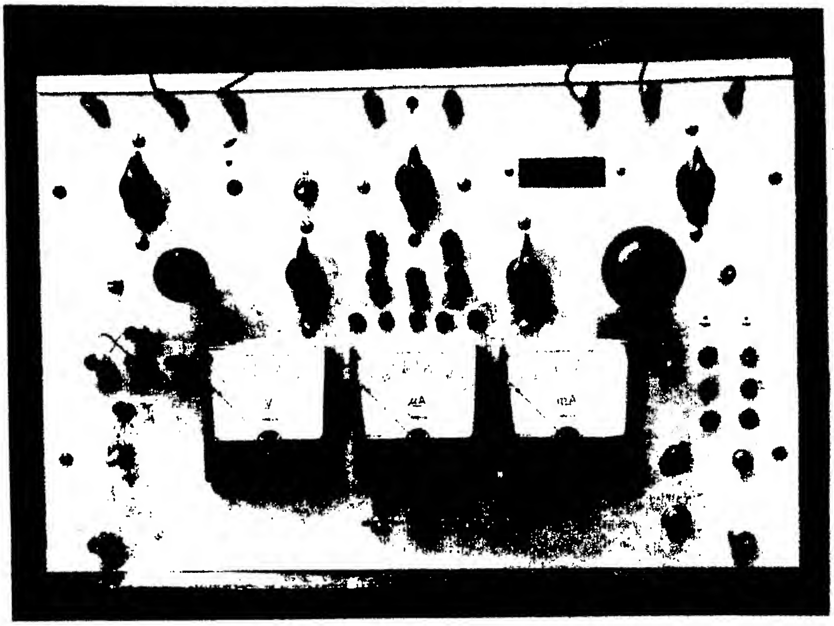
S.No.	Switching Angle of Fault Current (Degrees)	Transient Reach	Operating Time (msec.)
1	5	1.021	17
2	45	1.042	16
3	90	1.085	15
4	135	1.045	16
5	180	1.015	18
6	225	1.052	17
7	270	1.095	16
8	315	1.061	16
9	350	1.032	17

CHAPTER 5

DESIGN, FABRICATION AND APPLICATION OF DYNAMIC TEST BENCH

5.1 INTRODUCTION:

The performance of the distance relay, once designed and developed can be checked, either, by appropriate static signals or dynamic signals. The dynamic signals represent the actual system conditions and, also, take into account the transients and d.c. offset components present in the fault current. The complete power system can be simulated by the dynamic test bench, to a scale down model (low power level) hence, it becomes an invaluable device for testing the performance of distance relays. Dynamic test bench proposed by Hamilton et.al. [14], M/s General Electric (India) and M/s Robinson and Partners Ltd. was not found suitable for testing of the proposed relays as, a novel way of zone changing is incorporated in the present relaying scheme. Hence, a special type of dynamic test bench is designed and developed which provides the required signals for automatic zone changing and also, for the testing of the polyphase relay. It can simulate all the fault conditions, to predict the performance of the static relay during transient conditions also, i.e. to verify the accuracy of the relay with respect to its reach and range and the operating time with respect to switching angle of the fault current.



DYNAMIC TEST BENCH

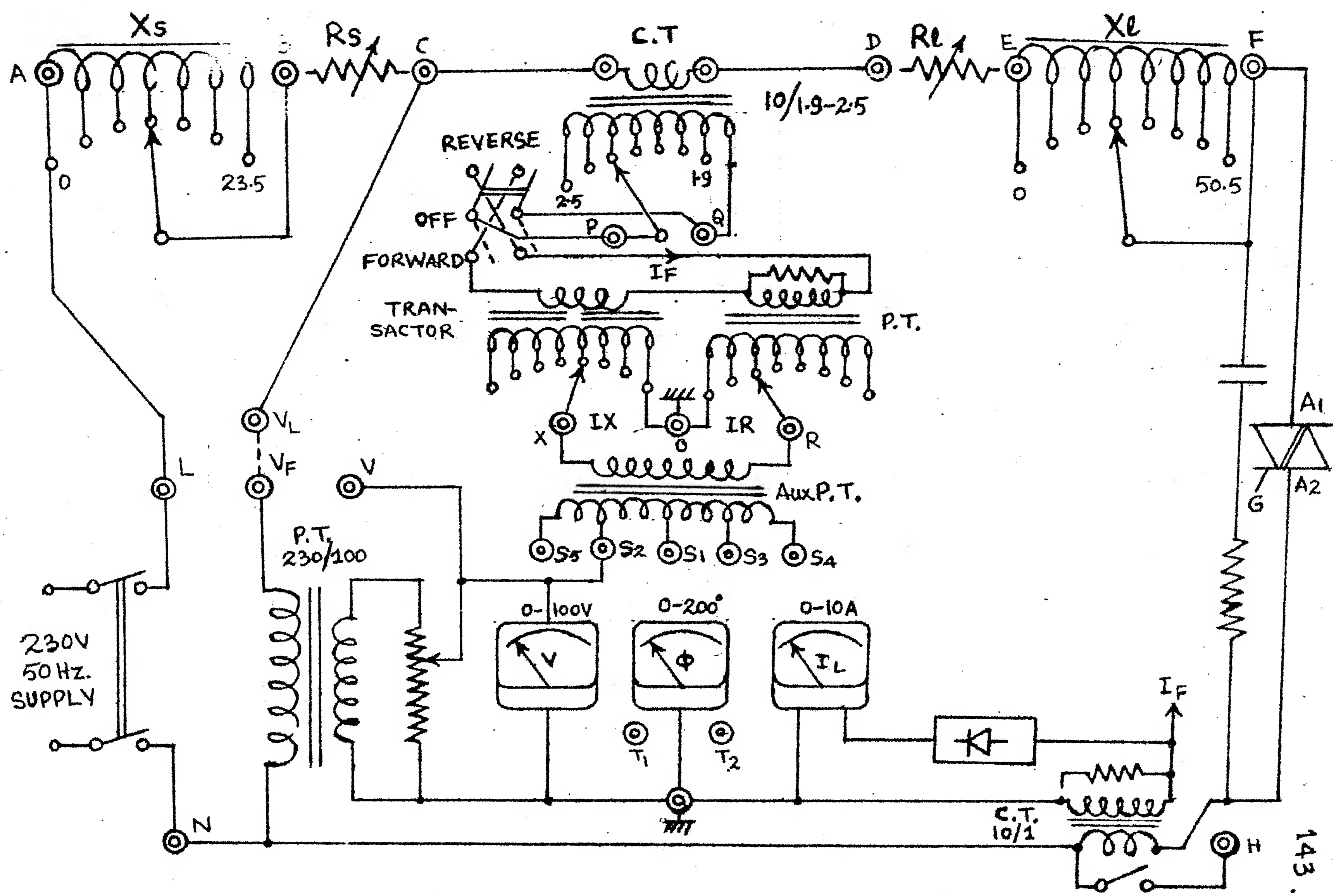


Fig.5.1 POWER & MEASURING CIRCUIT OF DYNAMIC TEST BENCH

square wave, the negative cycle of which is clipped by another diode. Positive (0-180^o) and negative (180^o-360^o) cycle control is achieved by a SPDT toggle switch with logic 0/1, through 4-NAND gates using IC 74C00. A triac is fired to simulate the fault condition, in which, the triggering can be delayed (phase angle control) by a monomulti (M-1) using a potentiometer (P-1) calibrated in degrees. Hence, the maximum time delay is 10 msec. which corresponds to an angle (α) equal to 180^o during each half of the cycle. The triggering of triac is initiated by a push-button switch (START) which enables the monomulti, giving firing pulses through NOR gates using IC 74C02. Carrier frequency (10 kHz) gating control is used for firing the triac through pulse transformer. As soon as the triac fires, a logic (1) is established at the input of the first NOR gate, hence, the firing pulses are maintained (continued). The power circuit can be turned off (short circuit or fault removed) by a push-button switch which stops the passage of 10 kHz pulses, at the base of the transistor, through the last NOR gate having logic (1) momentarily. Thus, the triac turns off at natural current zero. The presence of short circuit (fault simulation) is sensed by logic (1) using a precision detector, schmitt-trigger and peak detector. The operation of the point-on-wave selector can be understood by refering to the Fig. 5.3.

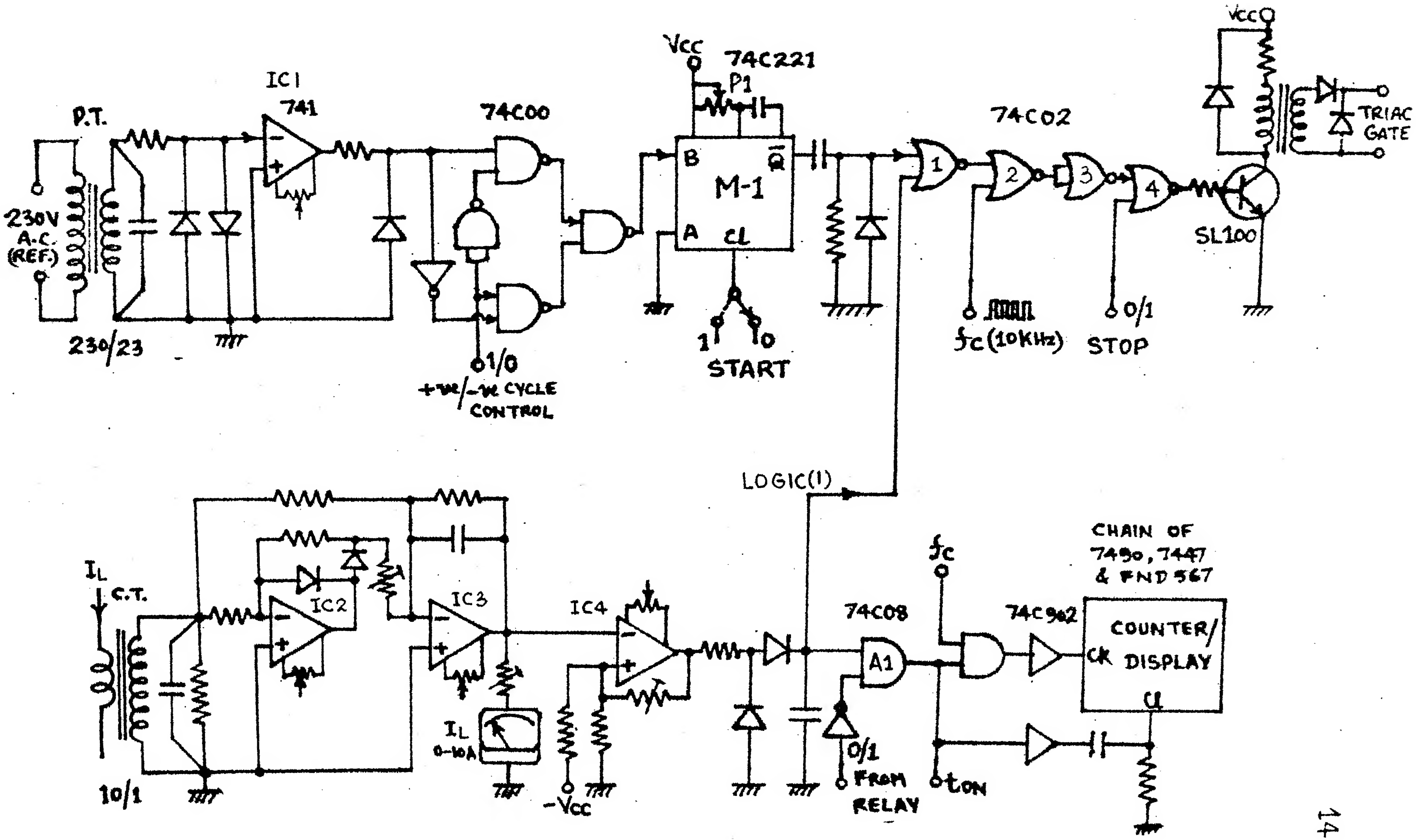


Fig.5·2 CONTROL & MEASURING CIRCUIT OF DYNAMIC TEST BENCH

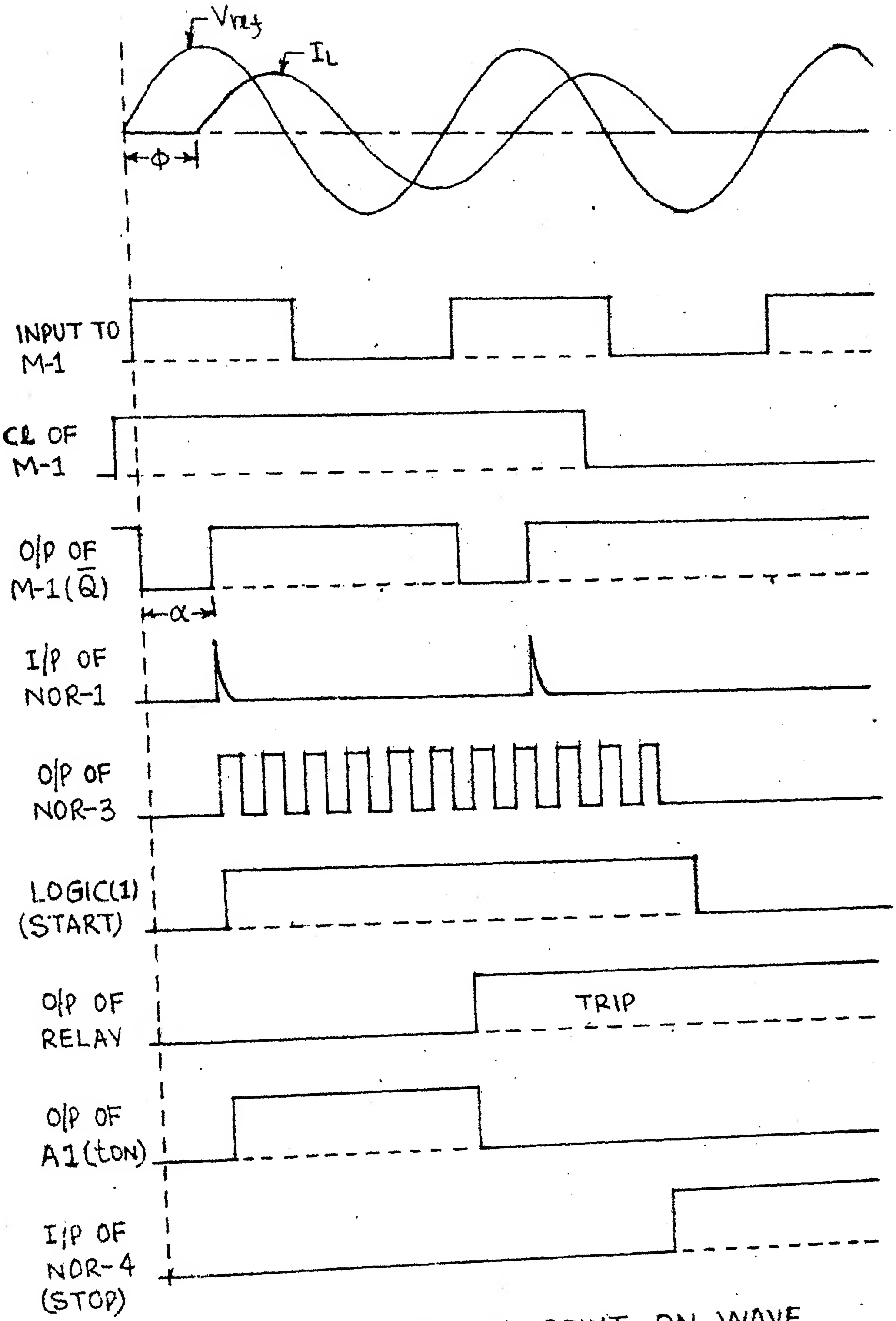


Fig. 5.3 OPERATION OF POINT ON WAVE SELECTOR

5.2.2 Relay Voltage and Current Simulator and Measurement:

A potential transformer of nominal turns ratio 230/100 and a current transformer of ratio 10/5 is designed and fabricated to supply the voltage and current to the relay unit. The C.T. turns ratio can be varied in the range from 1.9 to 2.5, in the step of 0.1, i.e. the ratios available are 1.9, 2.0, 2.1, 2.2, 2.3, 2.4 and 2.5. Thus, the change of ratio between two consecutive steps is approximately 4 to 5%, by which, the over and under-reach of the relay can be checked in the dynamic condition. The P.T. secondary is connected to a potentiometer (P-2) which is calibrated in percentage of voltage. Hence, the variation of P.T. ratio, together with C.T. ratio, can give five control over the reach of the relay under test.

The measurement of a.c. voltage is done by a rectifier bridge and a d.c. voltmeter for higher accuracy. The precision detector, as shown by lower circuit of Fig. 5.2, is also used to measure line currents. A DPDT switch, with centre off position, is used to inject the line current into any other transactor (replica impedance) so as to make the dynamic test bench more versatile. The same switch can also reverse the transactor current, so that, the directional property of the distance relay can be verified. The measurement of this

line current is done by a second C.T. with turns ratio 10/1, the secondary of which induces a voltage, proportional to line current across a low resistance, and, also provides IR reference vector for phase angle measurement etc.

5.2.3 Phase Angle Measurement:

The Electronic Phase Angle Meter is shown by Fig. 5.4. The phase angle between any two sine waves can be measured by 'plug-in' and the display is shown by analog d.c. micro-ammeter calibrated directly in degrees. An EX/OR gate is used to measure the phase-difference of the standardised sine wave. Two Op.Amp. are used to convert sine wave into square wave which can be made to pass to 'invertor' through switches S_1 and S_2. Thus, the polarity of any one input signal can be reversed at will which may be desirable in certain cases. The resolution of the phase angle meter is 2^o and the accuracy is better than $\pm 1\%$. Thus, the present phase angle meter, greatly, simplifies the measurement of phase difference with high degree of accuracy. The voltage sensitivity of the meter is from 100 mV to 100

5.2.4 Digital Time Measurement and Display:

The digital time interval meter can measure upto 999 msec. which could be the maximum operating time of zone-3 for high speed relaying. The basic principle of operation of this unit is as follows.

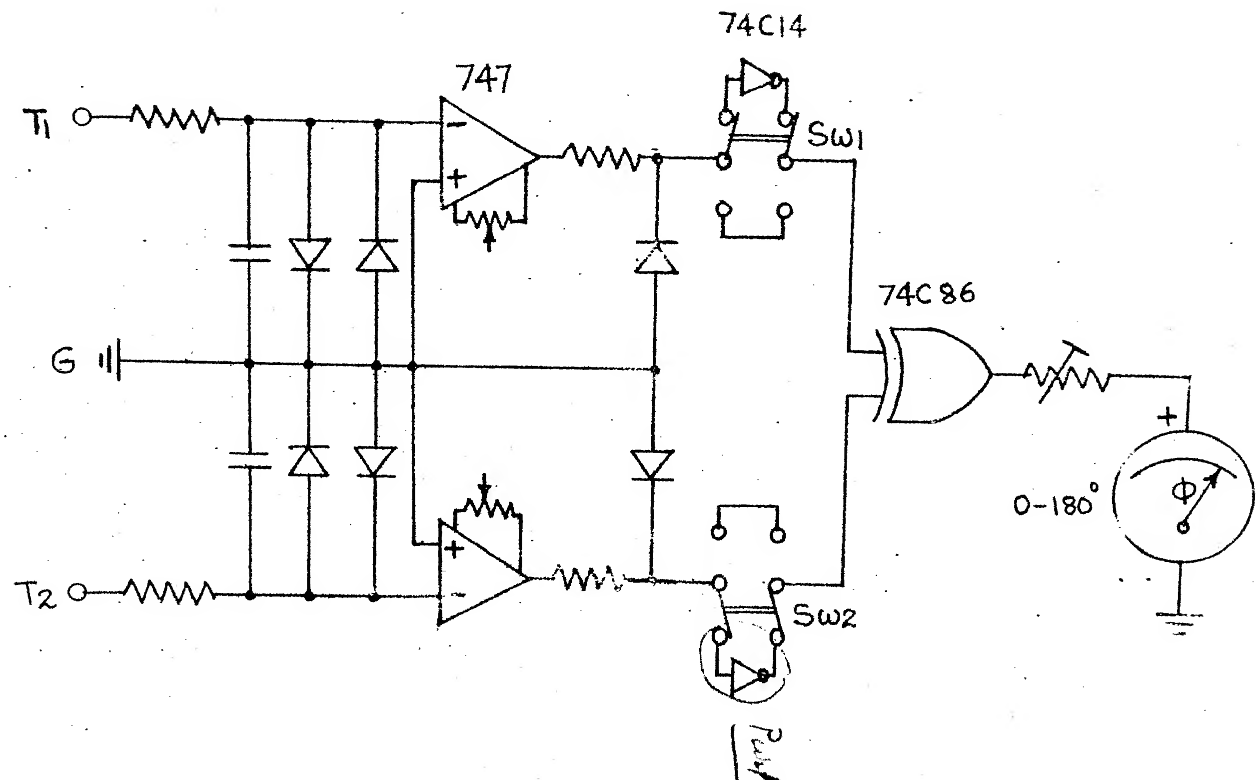


Fig. 5.4 ELECTRONIC PHASE ANGLE METER

A certain number of pulses (n) of known frequency (f_c) are counted during relay operating time (t_{on}), which gives the measure of time, thus,

$$t_{on} = \frac{n}{f_c} \quad \alpha \quad n \tag{5.1}$$

where f_c = constant.

A 4-stage decade counter is used with three, 7-segment display only. Input pulses (10 kHz) are gated for the time (t_{on}) to be measured. The fault initiation, with logic (1), start the counter and the relay operation, logic (1), stops the counter. It can be seen, that, the transient time is also included in relay operating time. As the line impedance is generally matched to replica impedance and the transactors themselve act as filters, the transient time could be 10 to 20 msec. which could be subtracted from the total operating time to get relay operating time. Four miniature sockets are provided on the control pannel of the dynamic test bench so that, t_{on}, f_c, I_L can be displayed on C.R.O. and the relay output (trip signal) can be injected to stop the counter. The same I_L signal is used as reference for phase angle measurements. The lower half of the Fig. 5.2 shows the time measurement and display device.

5.2.5 Source and Line Impedance:

Two iron cored tapped inductors, having air gaps, are used to simulate source and line reactance with continuous rating of 4 Amps. Provision is also made to insert line and source resistance, externally, so as to vary the source and line phase angles. The tappings of inductor are brought out to a rotary switch by which a desired source and line reactance can be inserted into the main circuit. The phase angles of the source and line reactors vary between 83^o to 87^o and 85^o to 88^o respectively.

These iron cored inductors are designed and fabricated with shell type arrangement from grain oriented silicon steel laminations. An air gap of about 3 mm was found adequate to give linearity over a wide range of reactance. The following expression can be used to calculate the number of turns to provide the required reactance, thus;

as $$IT = \frac{796}{\sqrt{2}} B_g l_g$$

Hence, $$T = \frac{565 B_g l_g}{I} \qquad (5.2)$$

and $$T_1 = T\sqrt{\frac{X_1}{X}} \qquad (5.3)$$

where,

I = maximum R.M.S. current

T = number of turns

T_1 = number of turns at reactance X_1

B_g = flux density in air gap in Wb/m^2

l_g = length of air gap in mm

X = $\frac{V}{I}$ = reactance

V = R.M.S. supply voltage

hence, turns for any other reactance (X_1) can be found out.

Table 5.1: Source and Line Impedances

ITEM	STEPS						
	1	2	3	4	5	6	7
X_S	3.0	4.8	9.5	15.5	19.5	23.5	-
r_S	0.40	0.52	0.73	0.95	1.07	1.20	-
X_L	5.0	10.8	15.8	20.5	30.5	40.5	50.5
r_L	0.41	0.58	0.75	0.87	1.11	1.32	1.52

5.2.6 Replica Impedance with 3-Zones:

An iron cored transactor, with air gap, is used to simulate replica reactance, the secondary of which has tappings to vary the reactance through a rotary switch. The replica

resistance is simulated by passing the primary current of the transactor through a low resistance and then, stepping up this voltage drop by a P.T. Tappings are provided on the P.T. secondary so as to vary the replica resistance through a rotary switch. This simulated impedance (R_R+jX_R) is isolated from the voltage circuit by an auxillary P.T., the secondary of which has 5-tappings to give a voltage proportional to kZ_{R1}, Z_{R1}, Z_{R2} and Z_{R3}. Hence, a 3-zone replica impedance is simulated in a novel way, without passing the line current directly through the inductor, as is normally done. The 1st zone replica impedance is Z_{R1}, kZ_{R1} is about 20% of Z_{R1}, Z_{R2} is 150% of Z_{R1} and Z_{R3} is 200% of Z_{R1}. The zone-1 impedance (Z_{R1}) can be further reduced by a factor of k which varies in steps from 0.2 to 1.0 by a rotary switch. The voltages IR_R, IX_R, kIZ_{R1}, IZ_{R1}, IZ_{R2} and IZ_{R3} are brought out on the control pannel, through banana sockets.

It can be observed from the above description that the replica reactance is produced ficticiously. The basic principle of the design of these reactances is, that if one ampere of primary current induces a voltage of one volt in secondary circuit, then the reactance of transactor is one ohm. The maximum value of replica impedance will depend upon, line impedance, i.e. the set impedance of the line to the balance point and C.T. and P.T. turns ratio, hence,

$$Z_R = \frac{Z_L \cdot kN_1}{N_2} \tag{5.4}$$

where,

Z_R = Replica impedance

Z_L = Line impedance up to the balance point

N_1 = C.T. turns ratio of dynamic test bench = I_L/I

N_2 = P.T. turns ratio of dynamic test bench = V_L/V

k = Per unit setting of voltage control

Table 5.2: Replica Impedances

ITEM	STEPS						
	1	2	3	4	5	6	7
X_R	5.0	10.0	15.0	20.5	25.5	29.5	35.0
r_R	23	43	60	75	96	105	140 ← why are th
R_R	1.0	2.5	3.8	5.0	7.5	9.5	13.5
r_R	9	22	32	42	60	77	115

5.2.7 Power Supply:

A well regulated, built-in power supply is made so as to provide ±12V d.c. and +5V d.c. for the Electronic Control, Measurement and Instrumentation purposes. The

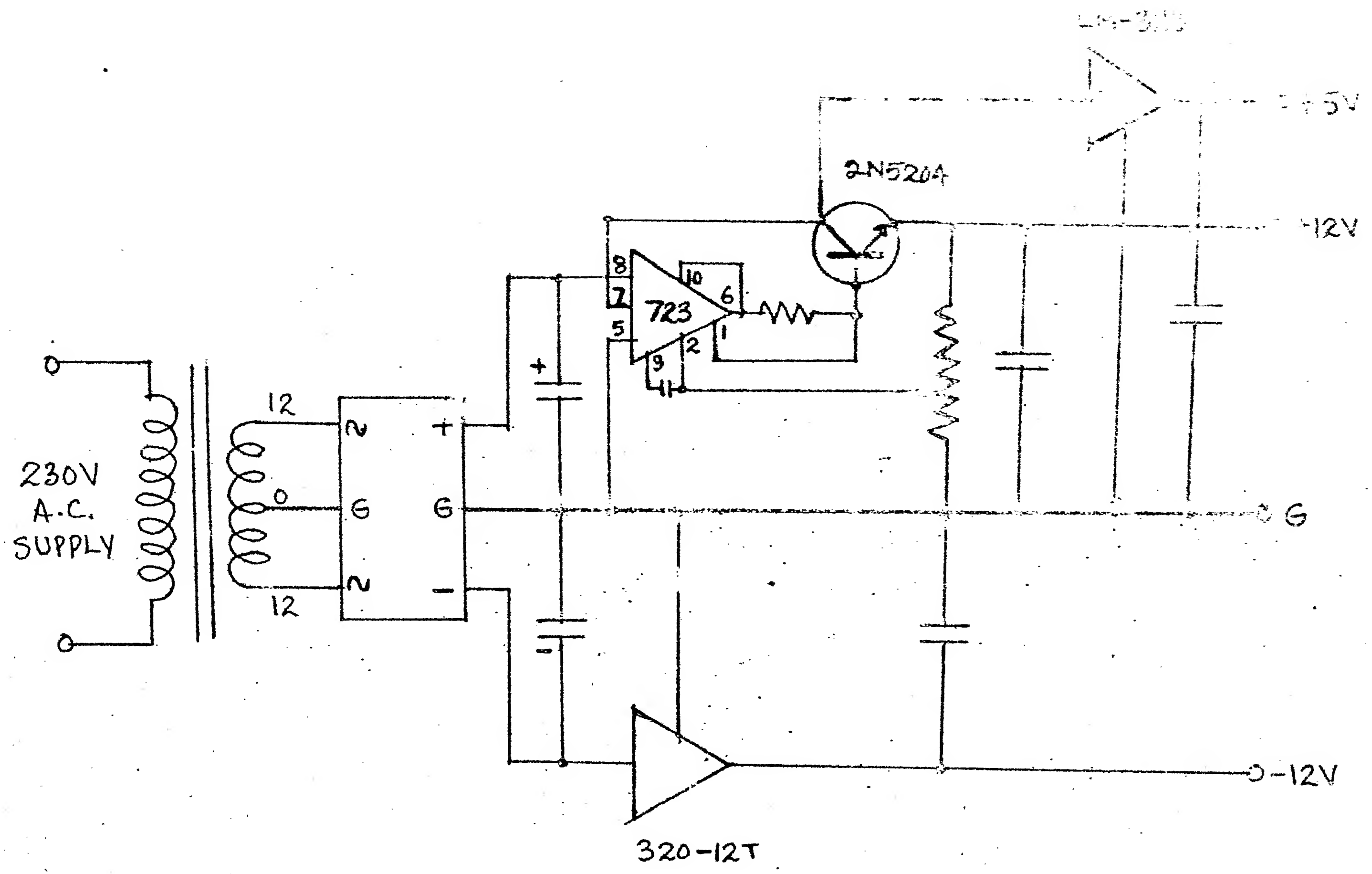


Fig. 5.5 CIRCUIT DIAGRAM OF POWER SUPPLY

circuit diagram is shown by Fig. 5.5. The IC-723 is used to provide +12V d.c. regulated supply whose current rating is boosted by a 'pass element' (power transistor). IC-320-12T is used to provide -12V d.c. regulated supply. A well regulated +5V d.c. supply, to drive the 7-segment LED display, is provided by using IC-LM323 voltage regulator. All these power supplies have built-in short circuit protection.

5.3 APPLICATION OF DYNAMIC TEST BENCH:

The front pannel layout of the dynamic test bench is shown by Fig. 5.5 and its power and measuring circuit diagram is shown by Fig. 5.1. A multi-tapping source inductor (X_S) and line inductor (X_L) is connected to terminals A-B and E-F respectively. Their magnitudes can be controlled by rotary switches, 'X_S control' and 'X_L control' respectively. The source and line resistances R_S and R_L can be connected externally between terminals B-C and E-F respectively. The external load can be connected to terminals F-H via a switch 'Ext.Load'. The 230V A.C. supply is connected to terminals L-N via a switch 'Mains ON'. The primary of main P.T. can be connected across line impedance ($R_L + jX_L$) via jumper between terminals V_L and V_F or it can be connected to the secondary of phase shifter. The secondary voltage of the main P.T. is measured by a voltmeter (V) and can also be connected to a

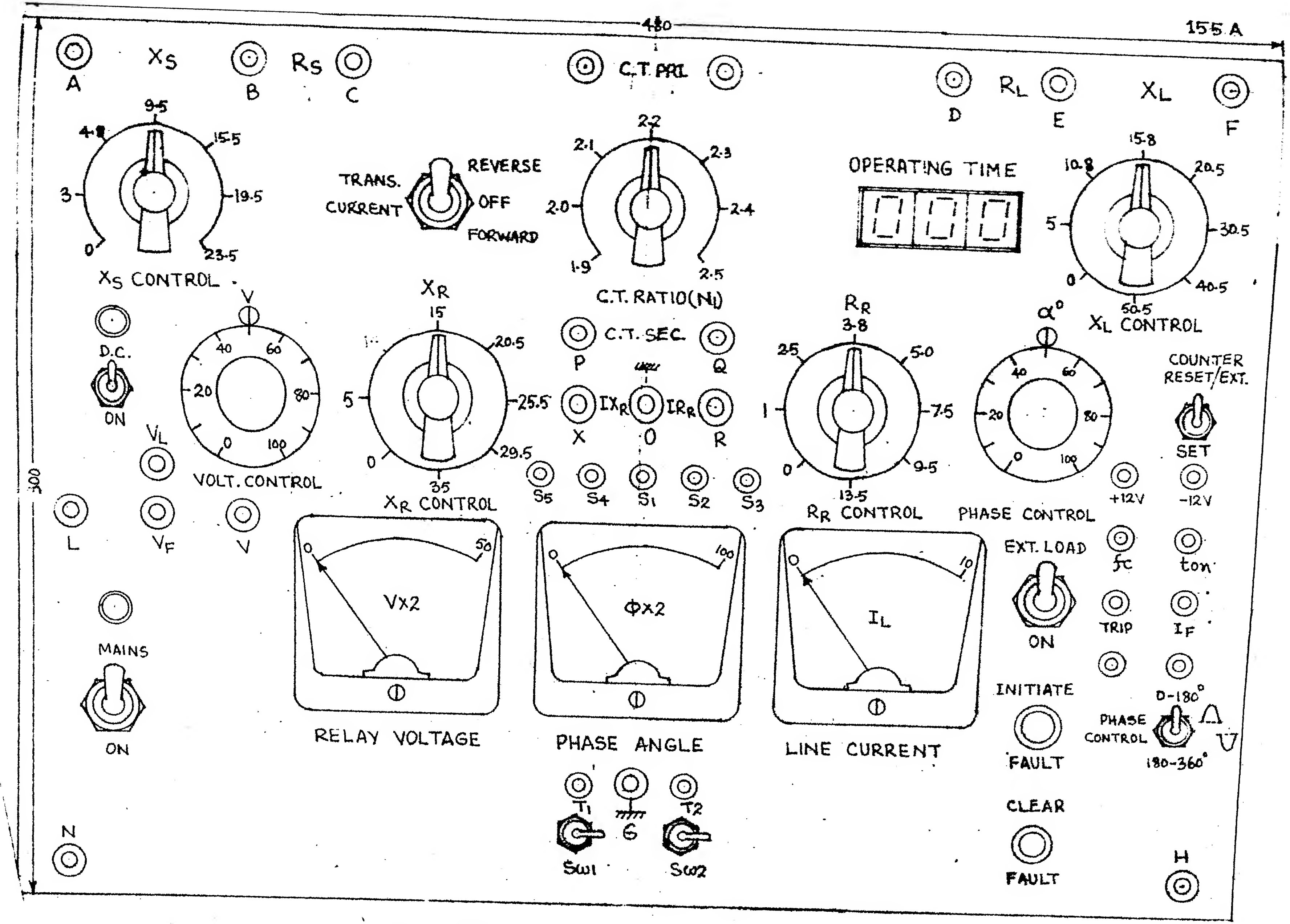


Fig.5.6 FRONT PANEL LAYOUT OF DYNAMIC TEST BENCH

relay through terminal (V). An ammeter (I_L) measures the fault current whereas the phase angle measurement is done by a 'phase meter' (Ø) via switches S_1, S_2 and terminals T_1-T_2. The transactor current (I_F) can be controlled by a rotary switch, 'C.T. Ratio' and the source current can be injected into an external transactor unit by a 3-position switch (Reverse-OFF-Forward) in OFF position through terminals P-Q. The secondary of transactor is connected to terminals X-R and hence, the replica reactance (X_R) and resistance (R_R) can be controlled by rotary switches 'X_R control' and 'R_R control' respectively. An auxilliary transformer (Aux. P.T.) is connected to terminals X-R, the secondary of which provides the required signals (S_1,S_2,S_3,S_4,S_5) for 3-zone operation of the proposed relaying schemes.

The fault can be initiated by firing a Triac through 'Fault-Initiate' push button switch and is cleared by 'Fault Clear' switch. The 'Phase Control' is the 'Point-on-Wave Selector' which can control the switching angle of fault current (I_L). Positive and negative cycle control is affected by a 'Phase Control Switch'. Four miniature sockets are provided, so that, clock frequency (f_c), operating time (t_{on}) and line current (I_L) can be observed and recorded. The fourth socket is used to inject the 'Relay Trip' signal, to

stop the digital time interval meter, so that, the operating time can be measured. A switch 'Counter Set/Reset' is provided to reset the counter.

5.3.1 Distance Relay Setting:

The impedance of transmission line on H.T. side depends upon the length of the line and also on the transmission voltage. If the line to be protected has an impedance of,

$$Z'_{L1} = (R' + jX') \tag{5.5}$$

then, the impedance setting on dynamic test bench will be

$$Z_L = \frac{0.8\ Z'_{L1} \times \text{C.T. ratio}}{\text{P.T. ratio}} = 0.8\ Z'_{L1}\ \frac{C_T}{P_T} \tag{5.6}$$

If the replica impedance angle (θ) and line phase angle (ϕ) are not equal then the value of replica impedance required will be

$$Z_R = \frac{Z_L}{\cos(\phi-\theta)} \times \frac{N_1 k}{N_2} \tag{5.7}$$

It should also be noted that, for line to ground fault, the relay voltage should be $V/\sqrt{3}$ and the value of line impedance setting is,

$$Z_L = (1 + \frac{K}{3})\ \frac{Z_R N_2}{k N_1} \tag{5.8}$$

Similarly, the value of relay voltage, for all types of phase faults, should be V and the line impedance setting is,

$$Z_L = \frac{2Z_R N_2}{kN_1} \tag{5.9}$$

where V is the line to line (i.e. delta) voltage on the secondary side of the P.T.

5.3.2 Relay Accuracy, Transient Over-reach and Range

The accuracy is defined as the ratio of impedance just causing operation of the relay to the set impedance when the fault takes place near the balance point, thus

$$\text{a) Accuracy } x = \frac{Z}{Z_R} = \frac{V}{IZ_R} = \frac{N_1 V}{I_L Z_R} = \frac{Z_L}{Z_R} \cdot \frac{N_1}{N_2} \tag{5.10}$$

If the relay trips by reducing the voltage, then,

$$x = \frac{kV}{IZ_R} = \frac{kN_1 V}{I_L Z_R} = \frac{Z_L}{Z_R} \cdot \frac{kN_1}{N_2} \tag{5.11}$$

Accuracy at any phase angle ($\emptyset$),

$$x = \frac{kV}{IZ_R \cos(\emptyset-\theta)} = \frac{kN_1 V}{I_L Z_R \cos(\emptyset-\theta)} = \frac{Z_L}{Z_R \cos(\emptyset-\theta)} \cdot \frac{kN_1}{N_2}$$

(5.12)

b) The transient over-reach

$$= \frac{\text{Impedance seen by relay with off set current}}{\text{Impedance seen without offset current}}$$

$$= \frac{Z_{OR}}{Z_{SR}} = \frac{k'N_1'}{kN_1}$$

$$= \frac{k'}{k} \Big|_{N_1 = \text{constant}} \tag{5.13}$$

where, k is the fraction of voltage applied in steady state condition and k' is the voltage applied during transient condition.

If $k' > k$ then overreach

and $k' < k$ then underreach

c) Range $Y = \frac{Z_S}{Z_R} = \frac{V_S - V_L}{I_L Z_R} = \frac{N_2(E-V)}{I_L Z_R}$ (5.14)

As all the variables are known or measured by dynamic test bench, the Accuracy, Transient overreach and Range can be calculated.

5.4 CONCLUSION:

The Dynamic Test Bench, designed, developed and fabricated by us, is simple, compact, accurate and self-contained and do not require any other auxiliary unit for its operation. All the proposed relaying schemes are tested on it and the results are in close agreement to the theoretical values.

CHAPTER 6

CONCLUSIONS

6.1 GENERAL:

The demand of electrical power has been increased manifolds during the last two decades which has necessitated the generation of large power far away from the load centres. This bulk power has to be transmitted over long distances by means of EHV/UHV transmission lines or tie lines. The power system reliability and transient stability depends upon how fast the fault is cleared which has necessitated the use of very fast,accurate, and efficient protection schemes. Solid state components has made it possible to achieve this requirement and hence, solid state relays are invariably used for the protection of transmission lines having voltages of 220 kV and above as they are more accurate, sensitive, robust, compact, durable, efficient and also immune to vibrations and shocks due to external causes than their counterpart i.e. the electromechanical relays.

The solid state relays, generally, use analogue techniques with block average comparison, in which the response time is a function of the fault location and the phase displacement between selected input signals. Block-spike comparison scheme

give fast response but has inherent drawbacks that, it is prone to maloperation due to spurious signals and therefore, not preferred for the protection of EHV transmission lines. The operating time of block average schemes is, generally, 20 msec (one cycle) upto a phase displacement of 60° but becomes infinity at the boundary conditions. This can create serious time coordination problem between different relays used in the protection scheme. Hence, if a relay, which has a constant operating time of less than 20 msec. any where upto the balance point can be designed and developed, it could solve all the problems associated with the protection of EHV/UHV transmission lines. Therefore, the main objective of the thesis had been; to design, develop~~e~~ and fabricate a transient free, 2-input block average coincidence comparator with, constant operating time of 15 msec (< one cycle), high noise immunity and Unaffected by power swing having simple circuitry and minimum hardware. The same basic comparator could be used in a variety of ways i.e. cosine and sine comparator and, with slight modifications, could be used as 3-zone single phase and 3-zone polyphase relay giving high accuracy to all types of shunt faults on three-phase systems.

A solid state comparator using CMOS logic gates and digital IC's, which is free from the most of the drawbacks of the existing schemes, had been designed, developed and

fabricated with a simple theory of operation. The symmetrical 2-input comparator can generate many important threshold characteristics such as, directional, restricted directional, angle impedance i.e. ohms, reactance, plane impedance, angle admittance i.e. mho and offset mho, restricted mho and elliptical etc. The variable angular critaria had been applied by the change of clock frequency and thereby, shaping the basic characteristics. The same comparator can be used as cosine or sine comparator giving flexibility and economy.

The basic 2-input comparator had been extended to provide multizonal operation in a novel way. Zone changing is done automatically depending upon whether the fault lies in Exp. zone-2 or zone-1. The relay normally operates with zone-2 time delay but its reach is changed to zone-1 if the fault lies in zone-1. However, back-up protection by zone-2 is always guarenteed. The operation in zone-3 is independent and provides a further back-up protection. The relay operates even if the voltage falls to 1% (close-up fault) but does not no result given operate when the voltage becomes zero which is an indication of open connection. The characteristics provided by this relay are classical mho in zone-1 and zone-2 but, elliptical in zone-3.

The same relay, with some modifications, can be used as a polyphase relay. Hence, in scheme-I tripplication of

three single-phase modules with their outputs OR gated give a polyphase relay. It also provides the classical characteristics as the operation is based upon 2-input comparators. Multi-input comparators can provide modified mho and quadrilateral characteristics. Hence, 4-input AND + NOR gates are used to convert the basic relaying scheme into a multi-input polyphase relay. The scheme-II gives modified mho characteristics with blinders by the use of 3-input signals only. The scheme-III gives the quadrilateral characteristics with 4-input signals, but, the fourth signal is dependent upon one of the three signals. All the three schemes had been found to be effective for all types of shunt faults on 3-phase lines and provide 3-zone operation in a novel way with cent percent discrimination and fast response.

A prototype, multipurpose, 3-zone polyphase relay had been designed and fabricated which is, in fact, a combination of three single phase (A,B and C) modules whose inputs are OR gated. This relay can be used in a variety of ways i.e., single phase operation in either zone-3, zone-2 or zone-1, single phase 3-zone operation, polyphase operation in any of the zone or in all the zones. It can be used as a 2-input comparator or multi-input comparator giving any desired pick-up characteristic.

A single-phase Dynamic Test Bench had been designed, developed and fabricated to predict the performance of the proposed relaying schemes. It represents a scaled down model of the power system, with built-in 'point on wave selector', phase angle meter and digital time interval meter. It also, has the facility, to vary and measure the line current and voltage and to provide required signals for 3-zone operation of the relaying scheme. Any type of fault condition can be simulated and the relay performance, with respect to range and switching angle of fault current, can be checked. The dynamic test bench designed and fabricated is compact, easy to use and versatile. All the relaying schemes had been tested on this dynamic test bench and their performance had been found to be satisfactory.

6.2 SCOPE FOR FUTURE WORK:

The use of CMOS logic gates and digital IC's.makes the relay circuit simplers, compact, reliable and also give better noise immunity, however, the use of 'high threshold logic circuits and IC's.' can further improve the performance of the relay and provide higher noise margin. The operating time of less than $\frac{1}{2}$ cycle is not feasible by the use of logic gates and digital IC's.alone. Further improvement by the use of digital techniques can be effected by proper choice of

components, relaying signals and operational philosophy to yield simple, fast, reliable and efficient protection schemes. Certainly, there is a possibility of developing a relay using travelling wave phenomena and similar other techniques which could be very fast in operation and yet reliable and efficient.

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Once such technique could be the use of digital computer or a microprocessor based 'On Line' protection which can definitely reduce the relay operating time to less than 5 msec. ($\frac{1}{4}$ cycle) with an advantage of clearing fault in shortest possible time as high speed circuit breaker of one cycle where it or less have become a common practice. A suitable algorithm, interface and hardware has to be generated and its long time durability and reliability is to be assessed before using a microprocessor or a minicomputer for practical applications such as the protection of EHV/UHV transmission lines. There is no doubt, that, in near future, digital relaying will prove to be better than conventional relaying schemes and will be accepted by 'Protection Engineers' as a primary means of protection.

APPENDIX

1. SPECIFICATIONS OF THE DIGITAL PHASE DISTANCE RELAY

1.1 RELAYING UNIT

1.1.1 Rated Voltage and current per phase : 100V, 10mA

1.1.2 Relay Elements per phase : 2

1.1.3 Mode of Operation as 2-input Comparator: Cosine and Sine

Mode of operation as Multi-input Comparator : Cosine

1.1.4 Variable Angular Criteria : $\pm 90^\circ$ to $\pm 30^\circ$ and 90° to 270°

1.1.5 Zone of Operation : Any one or all or as desired

1.1.6 Signal Handling Capacity : 2 to 4

1.1.7 Zone Indication : 2-LED on every-phase and zone

1.1.8 Operating Time of First-Zone: 15-20 msec. anywhere up to the balance point.

1.1.9 Pick-up characteristic : Mho, Modified Mho, Quadrilateral or any desired one.

1.2 TRANSACTOR:

1.2.1 Transactor Primary current : 5A per phase

1.2.2 Transactor Burden : 5VA per phase

1.2.3 Replica Impedance : 2.5Ω - 25Ω per phase

1.2.4 Replica Phase Angle : 80° - 30°

1.2.5 Signals Available : 6 per phase

2. SPECIFICATIONS OF DYNAMIC TEST BENCH

2.1 Source Impedance : 3-23.5 ohms at 83°-87°

2.2 Line Impedance : 5-50.5 ohms at 84^{o}-88^{o}.

2.3 Transactor Rating

2.3.1 Current Capacity and Burden : 5A, 10VA

2.3.2 Replica Impedance : 5-35 ohms

2.3.3 Replica Phase Angle : 80^{o}-30^{o}

2.4 Current Transformer

2.4.1 Primary Current : 10A

2.4.2 Secondary Current : 5A

2.4.3 C.T. Ratio : 1.8 - 2.5

2.5 Potential Transformer

2.5.1 Primary Voltage : 230V

2.5.2 Secondary voltage : 0 - 100V

2.6 Point on Wave-Selector : 0 - 360^{o}

2.7 Phase Angle Meter

2.7.1 Voltage Input : 100 mV - 100V

2.7.2 Range : $\pm 180^{o}$

2.7.3 Resolution : 2^{o}

2.8 Time Interval Meter (Counter) : 1 - 999 msec.

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